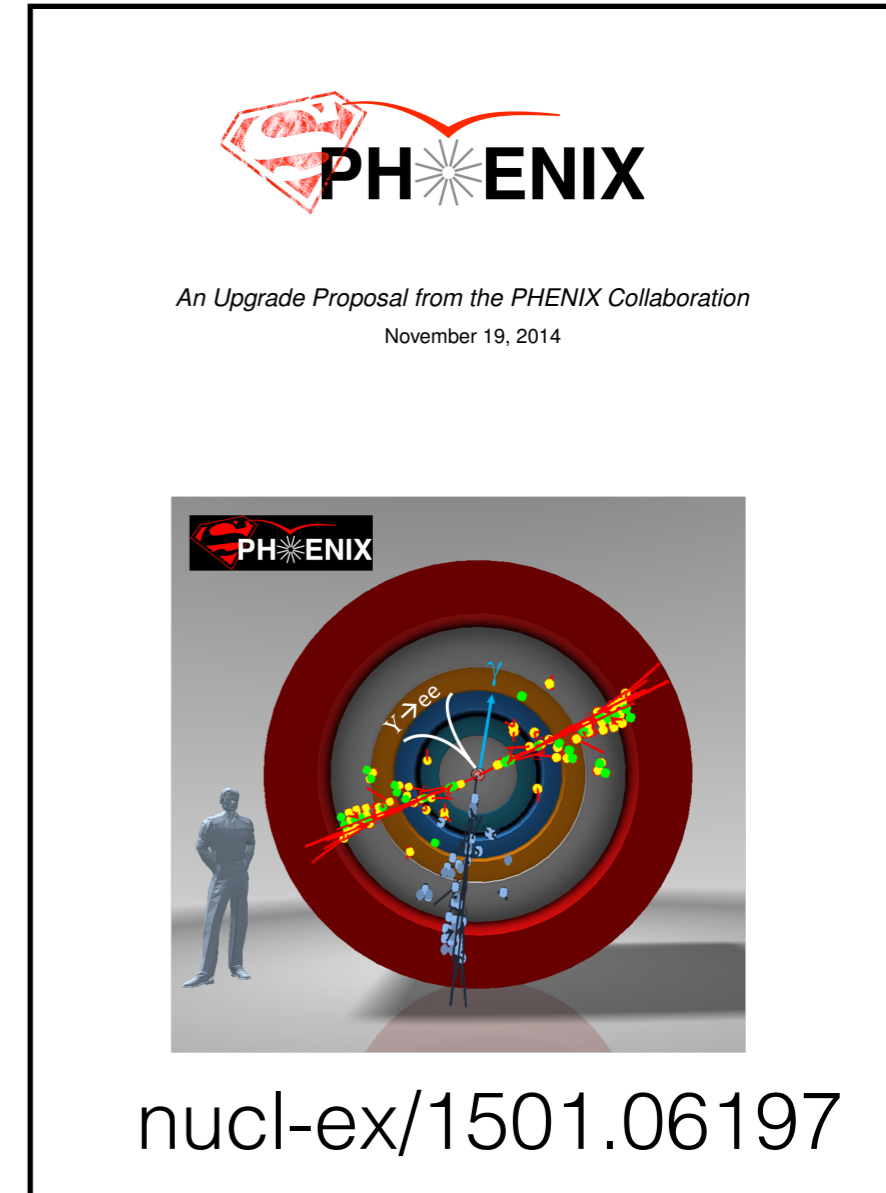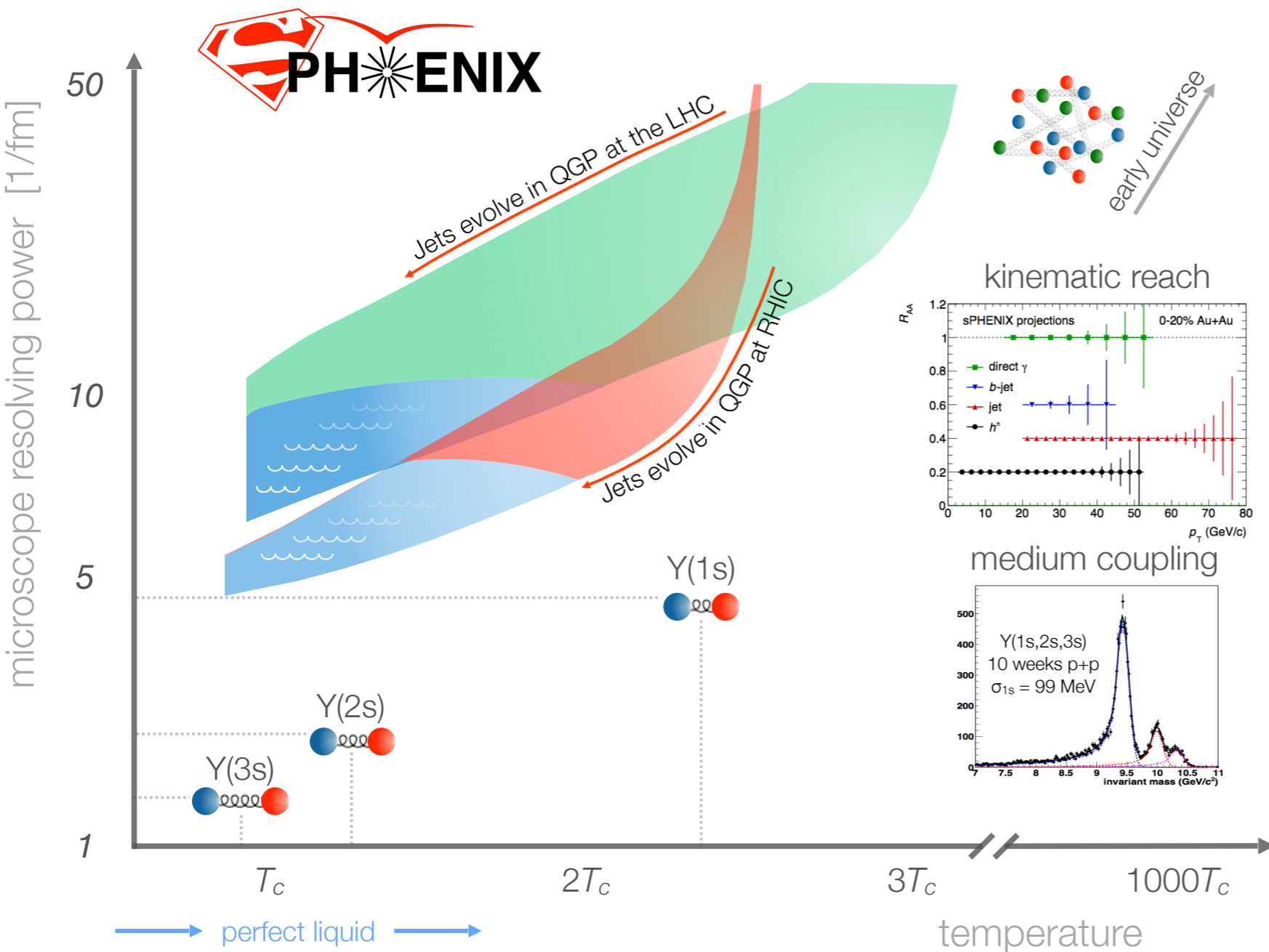# sPHENIX Science Case and the Reference Design

Dennis V. Perepelitsa
Brookhaven National Laboratory

16 June 2015
Large-Acceptance Jet and Upsilon
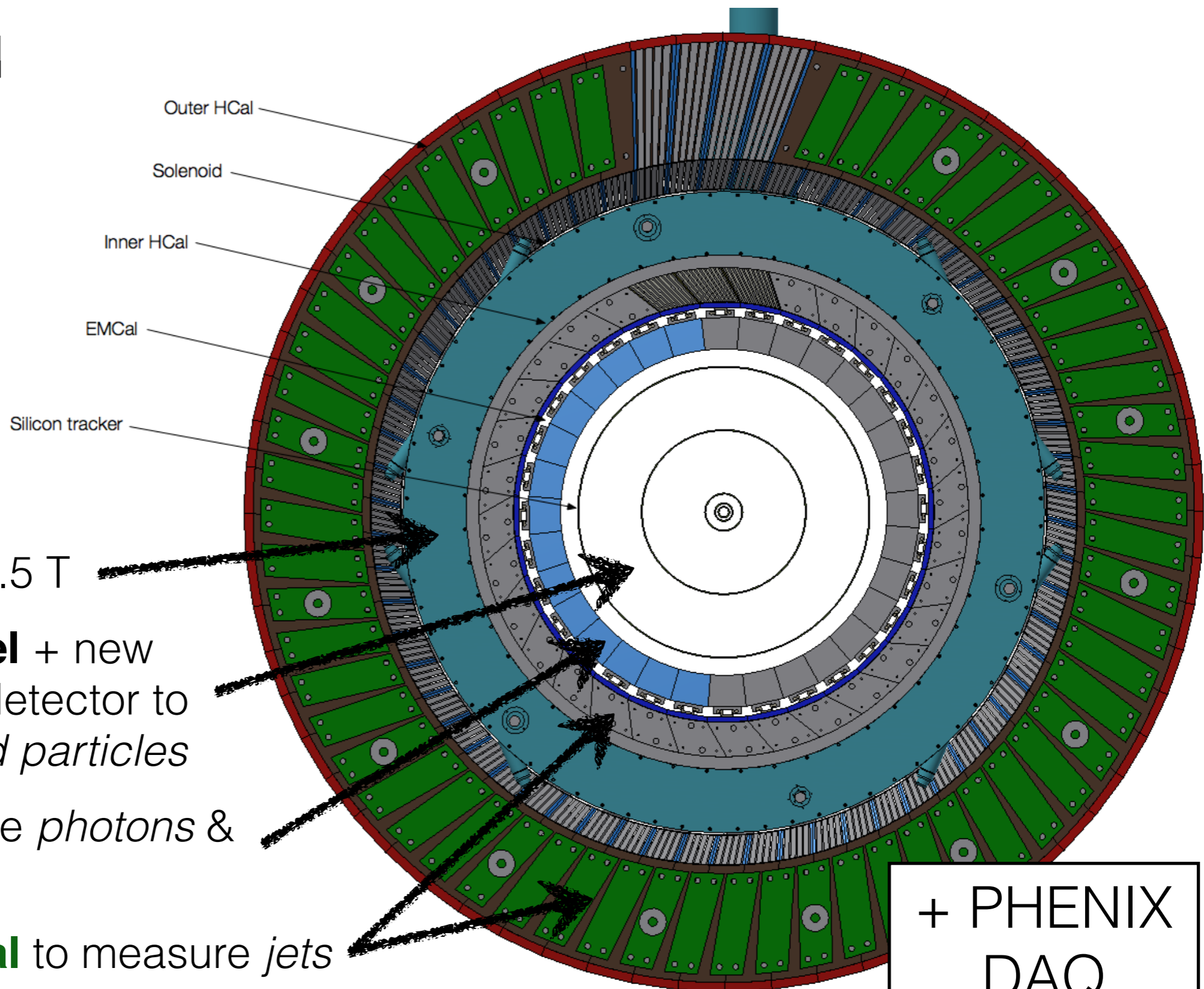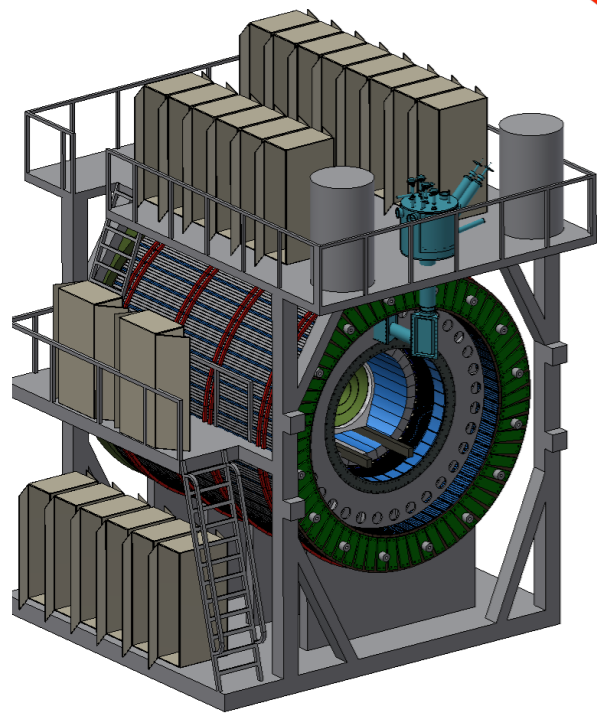Detector for RHIC Workshop

sPHENIX Science Case

nucl-ex/1501.06197

- Goal: quantitative understanding of the QCD medium over a range of length scales and temperatures

- Reference design developed to demonstrate access to the physics

  ➡ often, in response to guidance received by DOE Review Committee

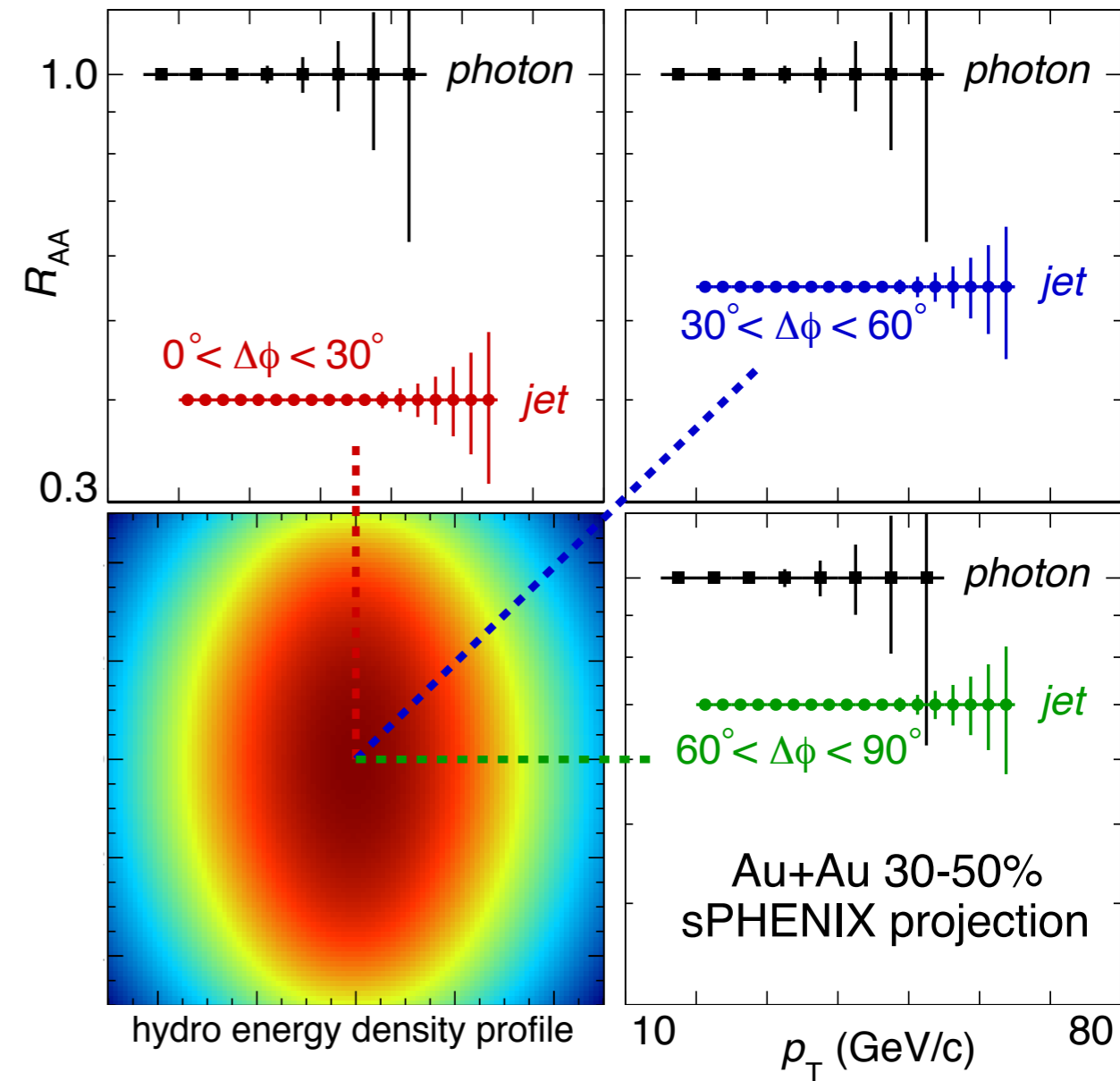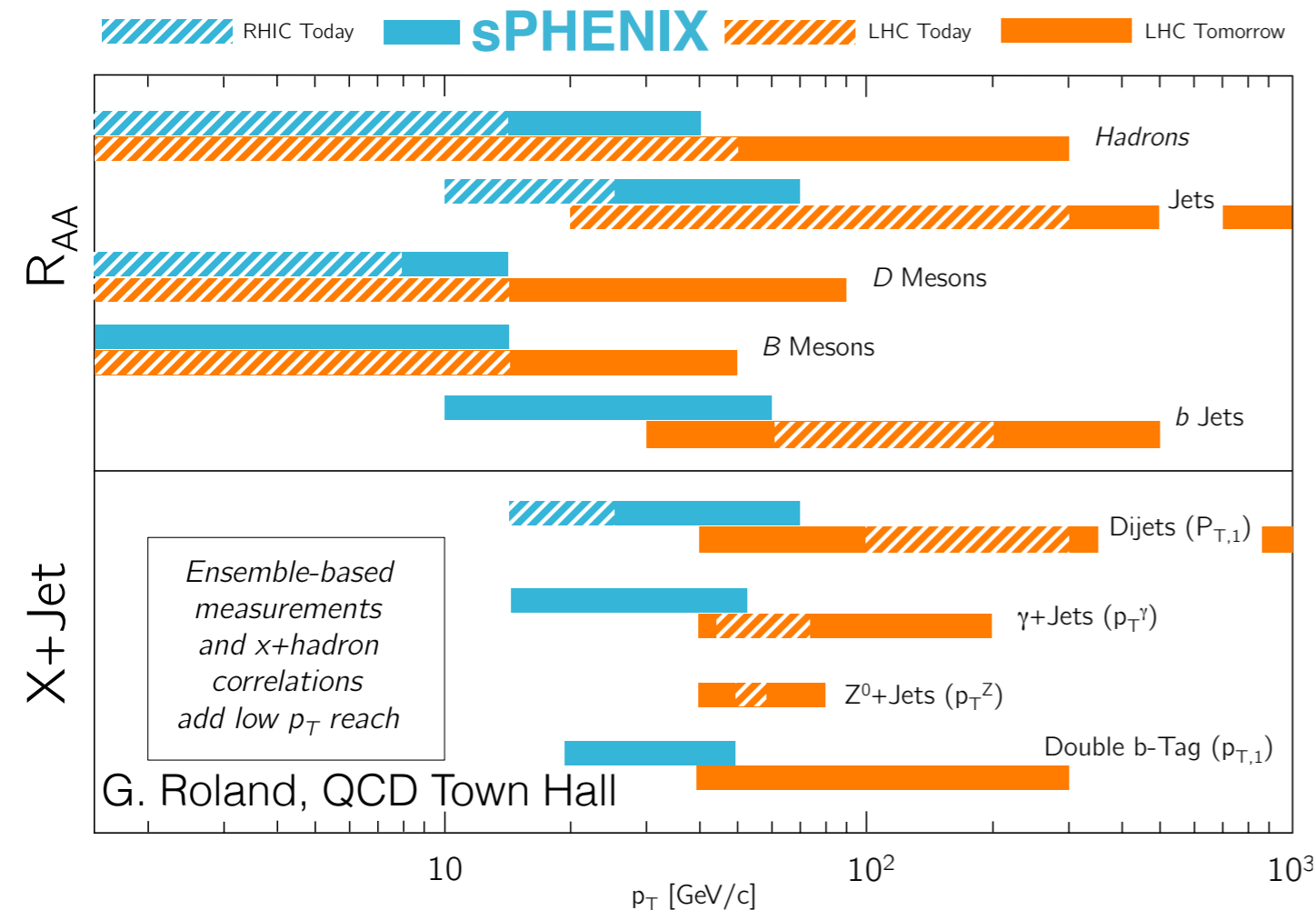# sPH✳ENIX Reference design

Reference design

- $|\eta|<1$, $\Delta\phi=2\pi$

- BaBar **magnet**, 1.5 T

- reconfigured **pixel** + new large area **strip** detector to measure *charged particles*

- **EMCal** to measure *photons* & *electrons*

- **Inner+Outer HCal** to measure *jets*

Outer HCal

Solenoid

Inner HCal

EMCal

Silicon tracker

+ PHENIX DAQ

Jets

unbiased & over a wide
kinematic range

Jet physics program

RHIC Today **sPHENIX** LHC Today LHC Tomorrow

R_{AA}

Hadrons

Jets

D Mesons

B Mesons

b Jets

X+Jet

Ensemble-based measurements and x+hadron correlations add low p_T reach

Dijets ($P_{T,1}$)

γ+Jets (p_T^γ)

Z^0+Jets (p_T^Z)

Double b-Tag ($p_{T,1}$)

G. Roland, QCD Town Hall

p_T [GeV/c]

R_{AA}

1.0

0.3

photon

$0° < \Delta\phi < 30°$

jet

photon

jet

$30° < \Delta\phi < 60°$

photon

jet

$60° < \Delta\phi < 90°$

hydro energy density profile

Au+Au 30-50%
sPHENIX projection

p_T (GeV/c)

10   80

- High-statistics, differential jet measurements over a wide kinematic range
  - ➡ measure at <u>low-p_T</u> (control fakes / resolution)
  - ➡ measure at <u>high-p_T</u> (capitalize on rate / triggering)
- Measure in p_T regions <u>*unavailable to LHC*</u>, while providing *crucial overlap*
  - ➡ *differential measurements* vs. centrality, reaction plane, etc…

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Jet measurement

γ-jet balance

frag. func.

dijet asym.

spectra
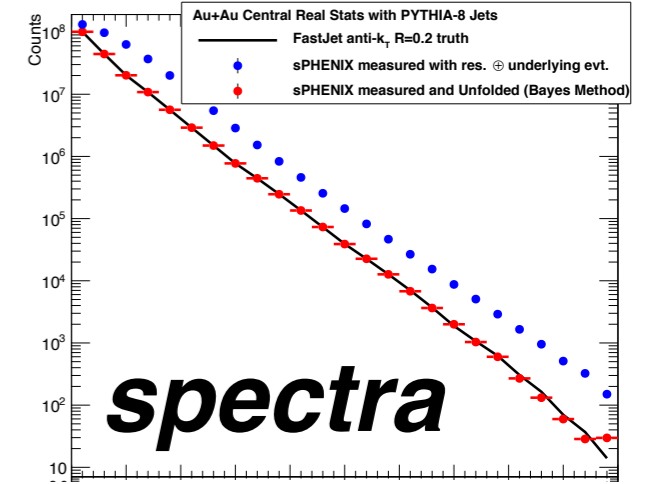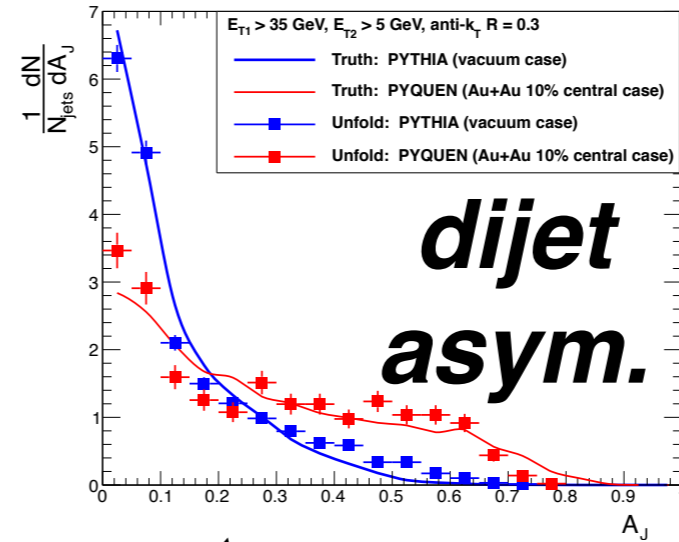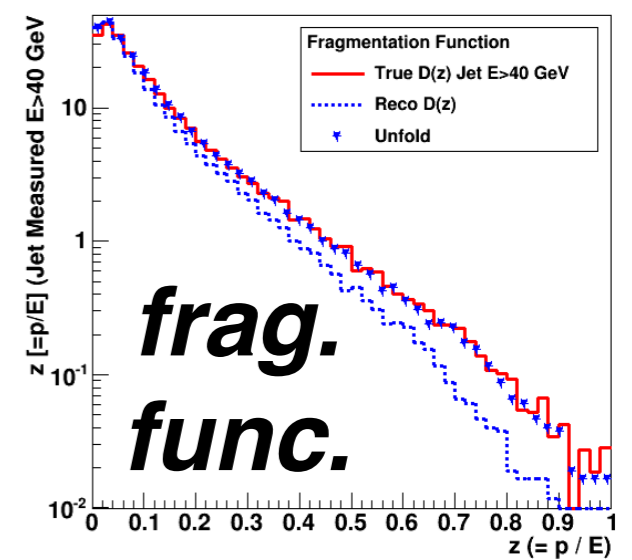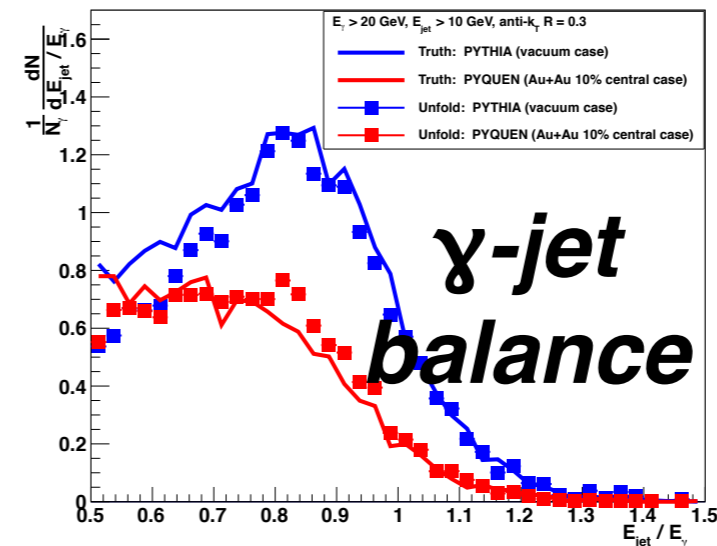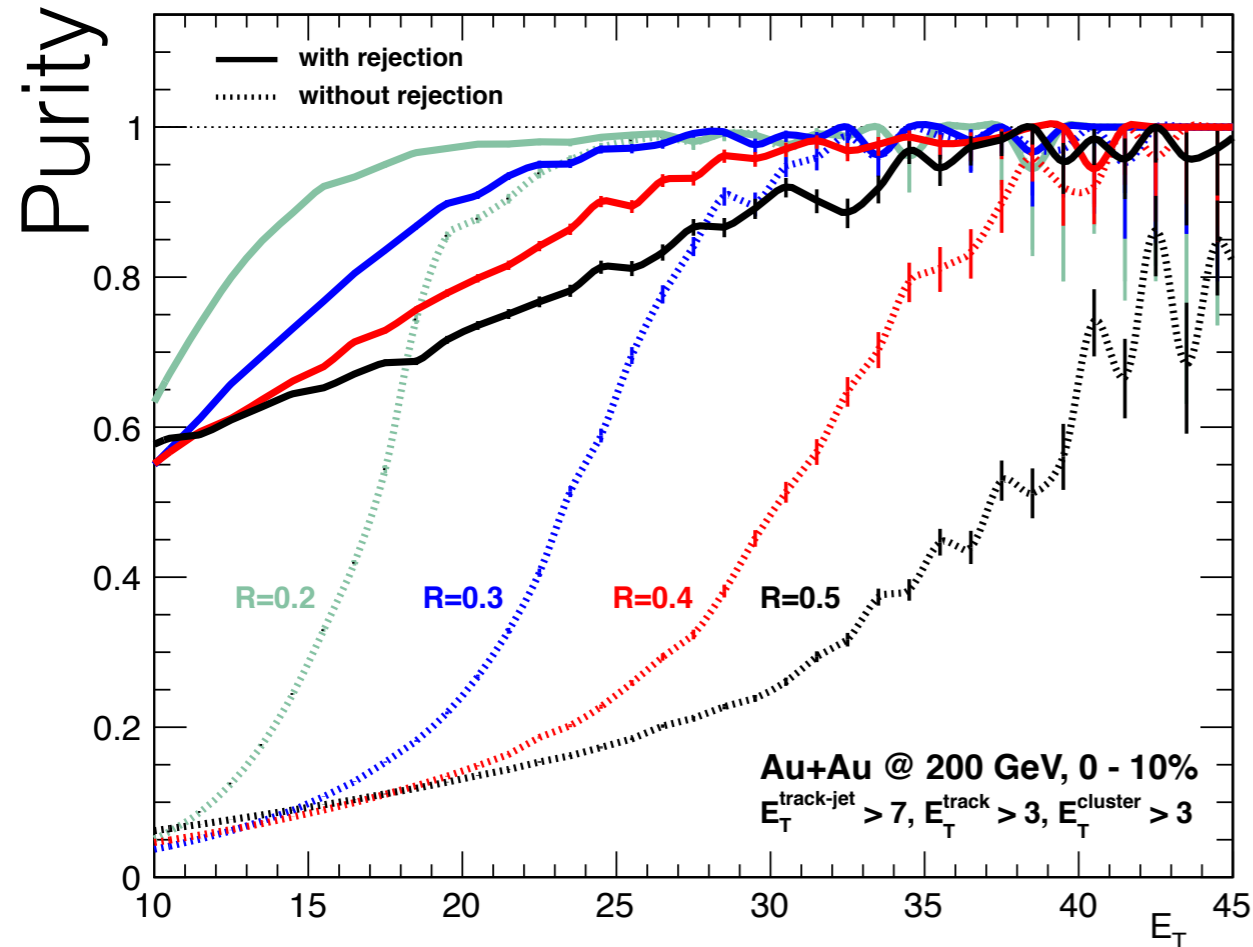
Unfolding tests

- Jet reconstruction & ATLAS-style background subtraction w/ *segmented hadronic calorimeter*

  ➡ successful *separation* of real jets from HI UE background, with additional rejection techniques *extending p_T range*

  ➡ *resolution on measured jet energy* minimizes systematic uncertainties

- Other options ("particle flow", statistical UE jet subtraction) also being explored

Jets: rate
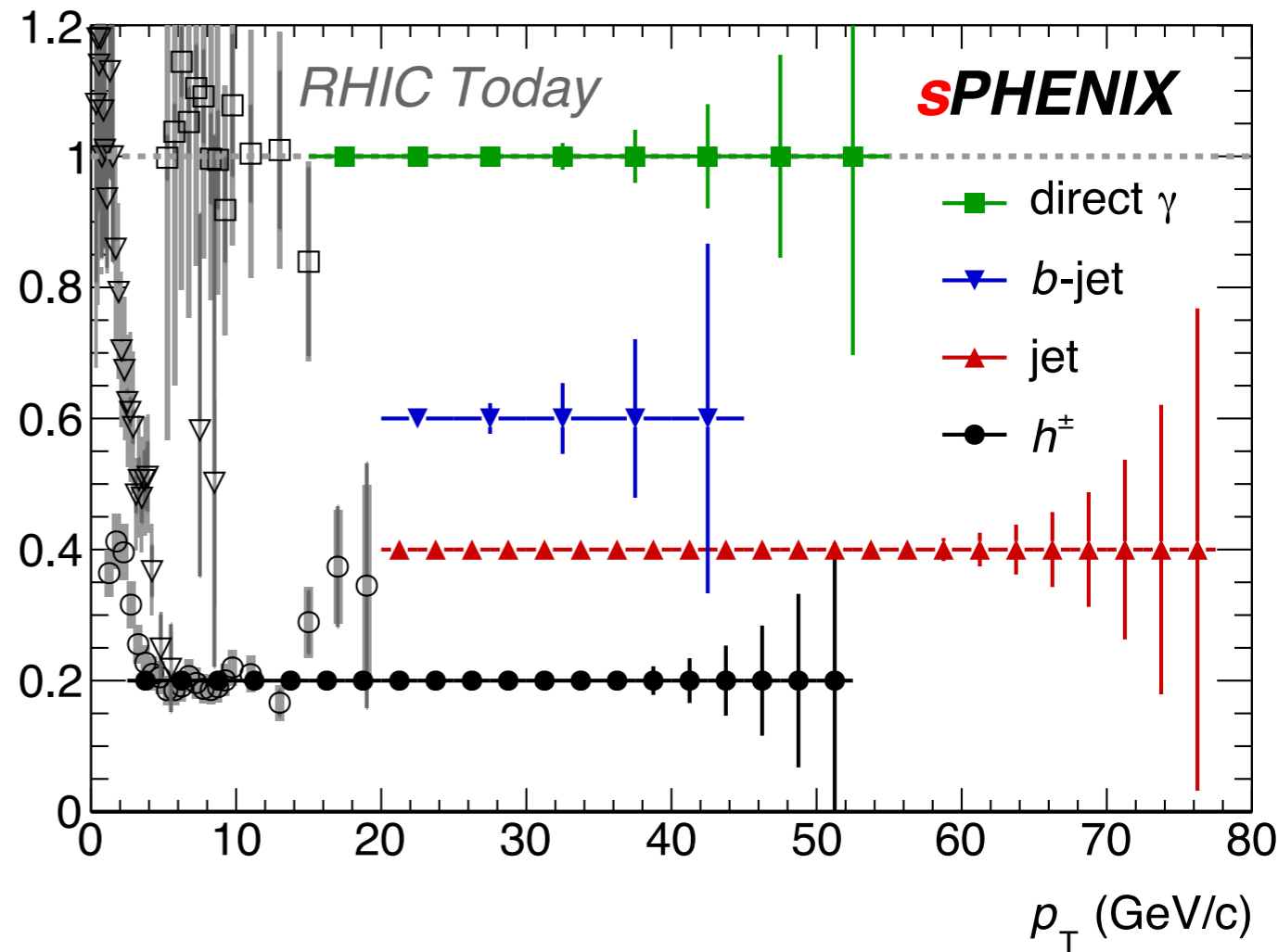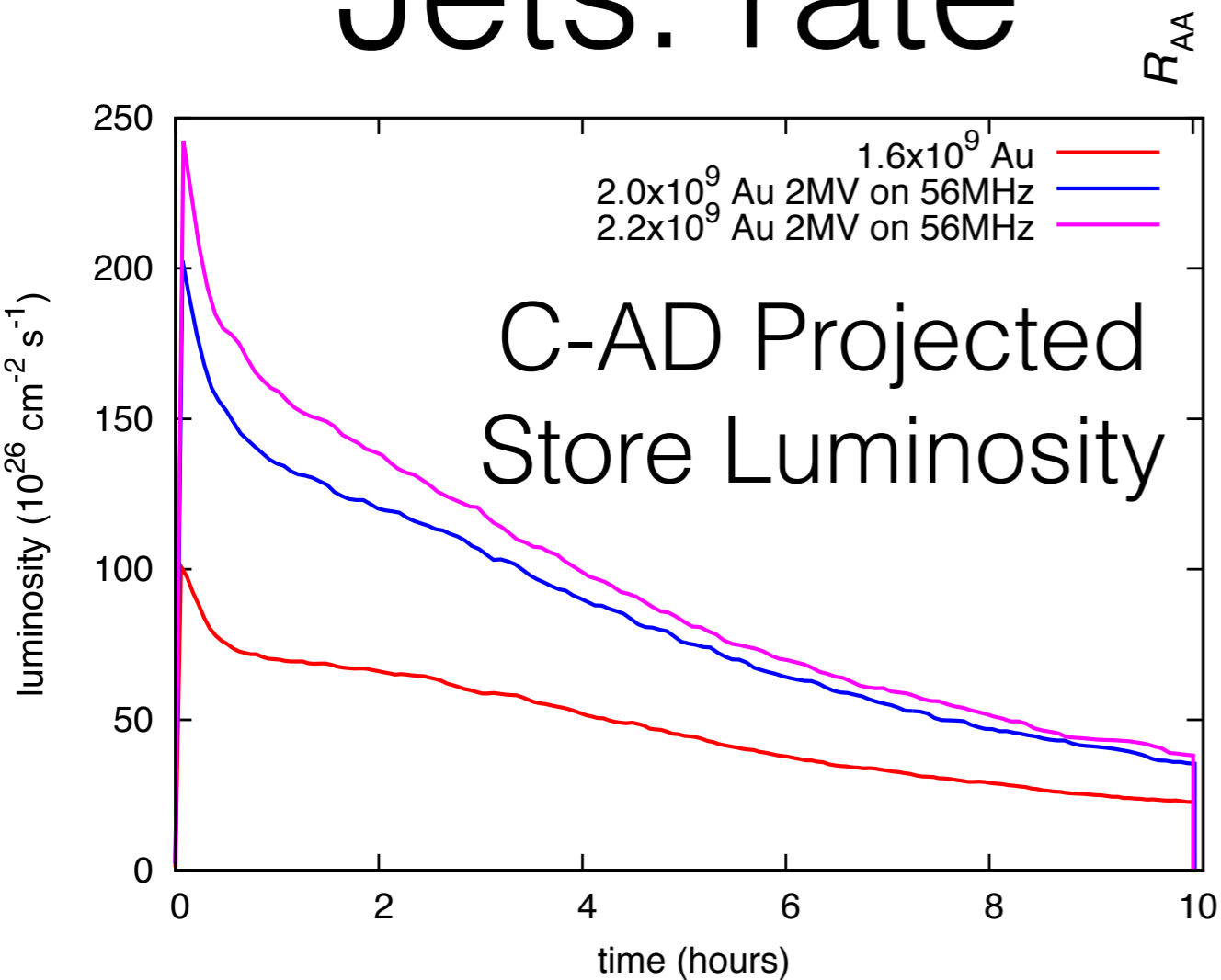
- Latest projected luminosity for 22 weeks Au+Au physics run: _0.1 trillion_ minimum bias Au+Au events with $|z_{vtx}| < 10\text{cm}$

  ➡ _large untriggered sample_ reduces biases and systematics

  ➡ _0.6 trillion_ w/ mild triggering and no z_{vtx} requirement

- Existing PHENIX DAQ infrastructure samples _15kHz_ at Level-1

  ➡ extension of kinematic range _far beyond existing RHIC_

Jets: trigger

Legend (upper-left plot):
- ■ Quark jets, EM+HCal
- ● Gluon jets, EM+HCal
- ■ Quark jets, EMCal only
- ● Gluon jets, EMCal only

G4 Simulation
PYTHIA $p+p$ 200 GeV

$E > 10$ GeV in 0.8×0.8

Y-axis: Trigger efficiency
X-axis: Jet E_T (GeV)
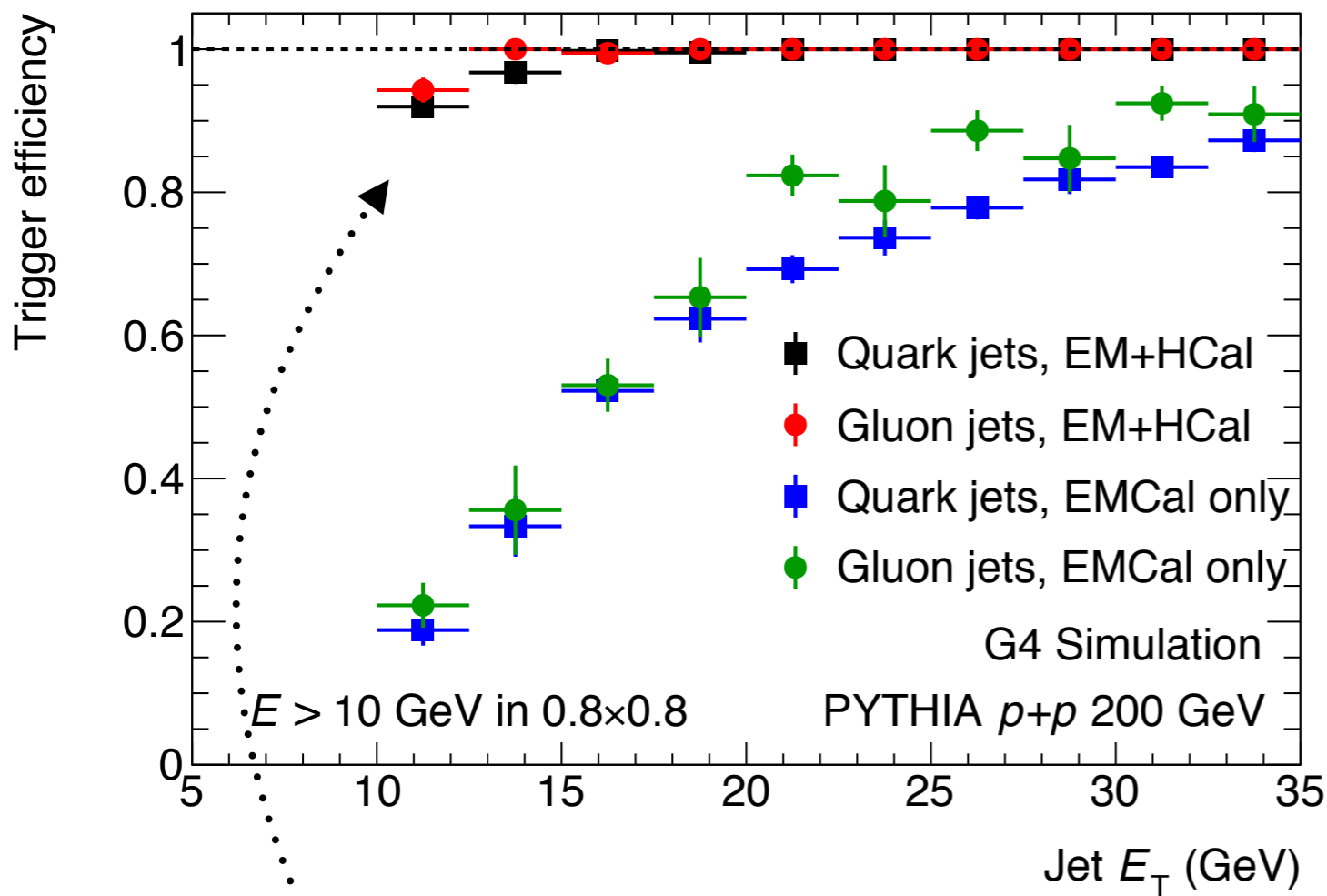
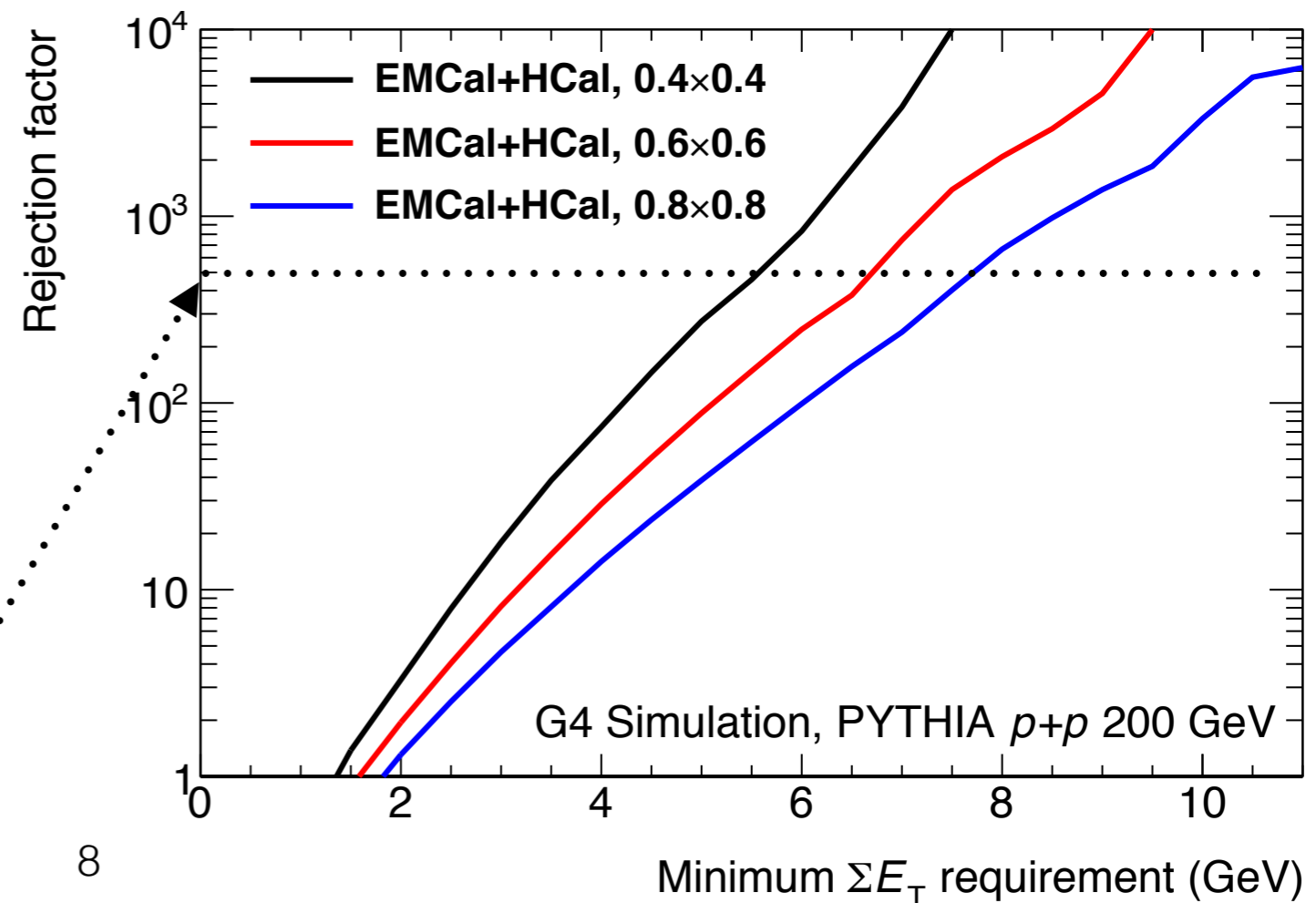- Triggering needed in $p+p$ running to sample the equivalent *NN* luminosity

  ➡ require *unbiased* sample of jets *down to low p_T*

- Solution: wide-area EMCal+HCal "**jet patch**" triggers

  ➡ require 10 GeV in sliding tower window of $\Delta\eta \times \Delta\phi = 0.8 \times 0.8$

  ➡ 100% efficiency with *no flavor dependence*

- Rejection factors for MB $p+p$ events are sufficiently high

Legend (lower-right plot):
- — EMCal+HCal, 0.4×0.4
- — EMCal+HCal, 0.6×0.6
- — EMCal+HCal, 0.8×0.8

G4 Simulation, PYTHIA $p+p$ 200 GeV

Y-axis: Rejection factor
X-axis: Minimum ΣE_T requirement (GeV)

Upsilons

with high statistics and
good mass resolution

Upsilon physics

CMS PbPb $\sqrt{s_{NN}}$ = 2.76 TeV

R_{AA}
- Υ(1S), stat. unc.
- Υ(1S), syst. unc.
- Υ(2S), stat. unc.
- Υ(2S), syst. unc.

L_{int} = 150 μb^{-1}
$|y| < 2.4$
p_T^μ > 4 GeV/c

nucl-ex/1208.2826

50-100% 40-50% 30-40% 20-30% 10-20% 5-10% 0-5%

N_{part}

R_{AA} = 0.06
for Υ(3S)
not shown!

LHC

RHIC

Upsilon Melting
— Hydro Pb+Pb 2.76 TeV
— Hydro Au+Au 200 GeV
— Hydro Al+Al 200 GeV
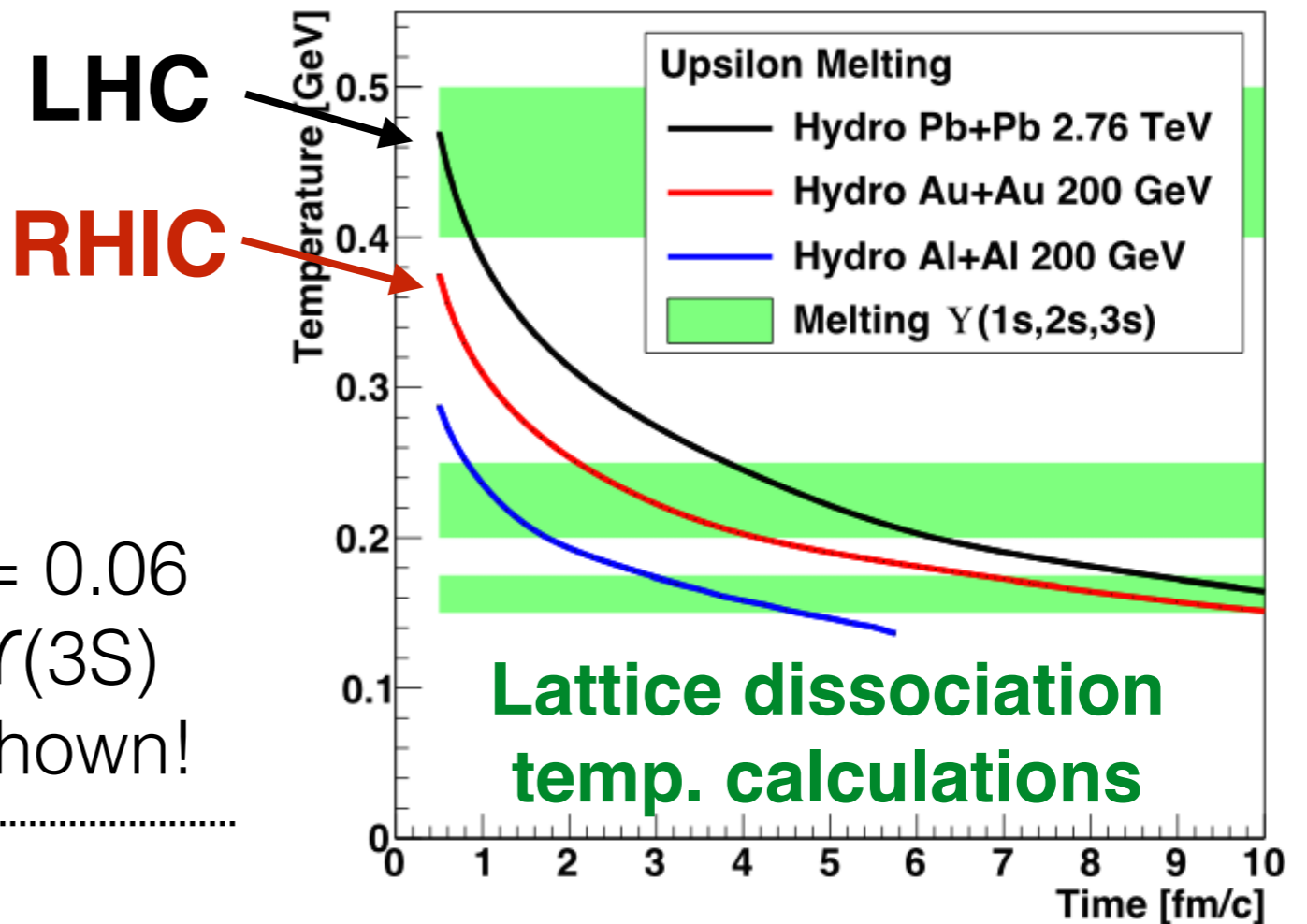Melting Υ(1s,2s,3s)

Temperature [GeV]

Time [fm/c]

Lattice dissociation temp. calculations
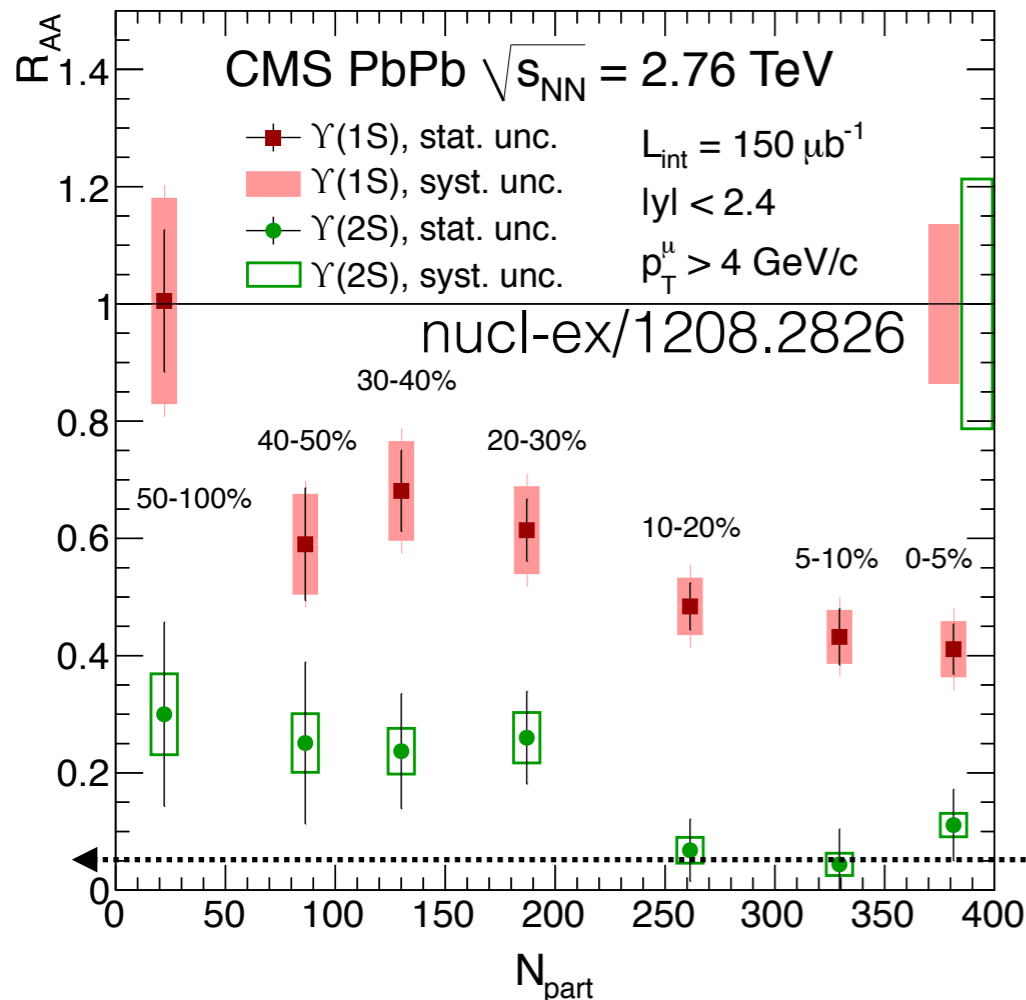
- Upsilon states probe the medium at _multiple (thermal) scales_

  ➡ similar nPDF effects and comparable yields

  ➡ minimal recombination at RHIC & LHC

- At the LHC: suppressed Υ(1S), but even stronger effects for forward Υ(1S) and central Υ(2S),Υ(3S)

  ➡ crucial lever arm provided b   color s

PHENIX Υ (1S+2S+3S)
STAR Υ (1S+2S+3S)
$|y|<0.5$

CMS PbPb $\sqrt{s_{NN}}$
- Υ(1S)
- Υ(2S)

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Upsilons: mass resolution

Left plot legend:
- **Total**
- Backgrounds:
- **D Y,B B̄,D D̄**
- **D+h,B+h,h+h**

1 RHIC AuAu run
100 B MB events
$e^+ e^-$ decays
$-1 < \eta < 1$
π rejection 90
centrality 0-10%
N_{coll} scaled

Right plot labels:
Au+Au 0-10%
10B events

(22 week projection)

- ++,-- subtracted
- Y(1S)
- Y(2S)
- Y(3S)
- correlated bkg

invariant mass (GeV/c^2)
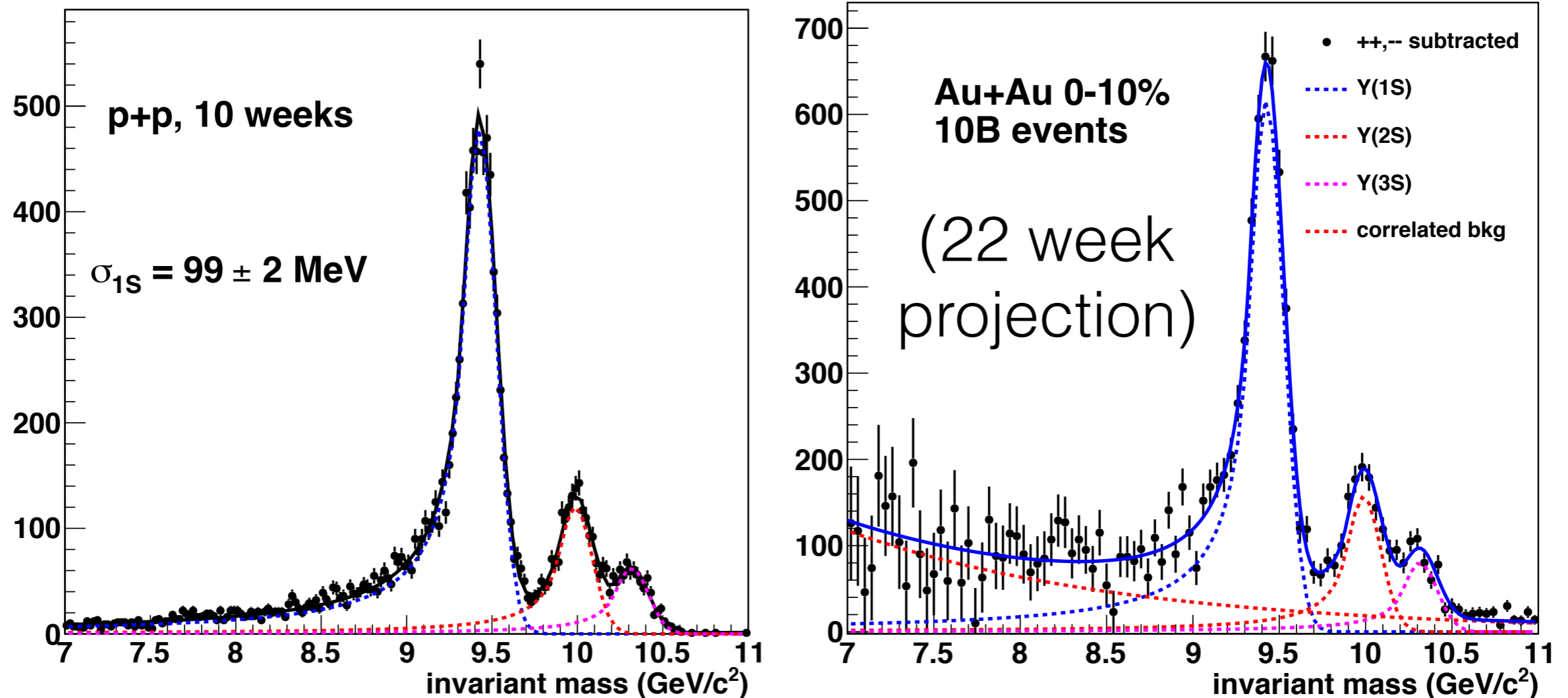
- Target: mass resolution of <100 MeV in *pp* collisions
  - ➡ allows clean separation of Upsilon states
- Achieved by optimizing tracking configuration:
  - ➡ low mass, to minimize Bremsstrahlung tails
 - ➡ large-radius layers to improve momentum resolution

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Upsilons

p+p 10 weeks
- ● Υ(1S)
- ● Υ(2S)
- ● Υ(3S)

Rejection factor for MB events

Rejection, EMCal 2×2
Efficiency, EMCal 2×2
Rejection, EMCal 4×4
Efficiency, EMCal 4×4

ficiency for $E=4.7$ GeV electrons

Strickland & Bazow
NP A879 (2011) 25
- ● Υ(1S)
- ● Υ(2S)
- ● Υ(3S)
- —— $4\pi\eta/S=1$
- - - - $4\pi\eta/S=2$
- ⋯⋯ $4\pi\eta/S=3$

R_{AA} vs. p_T

- Υ(1S)
- Υ(2S)
- Υ(3S)
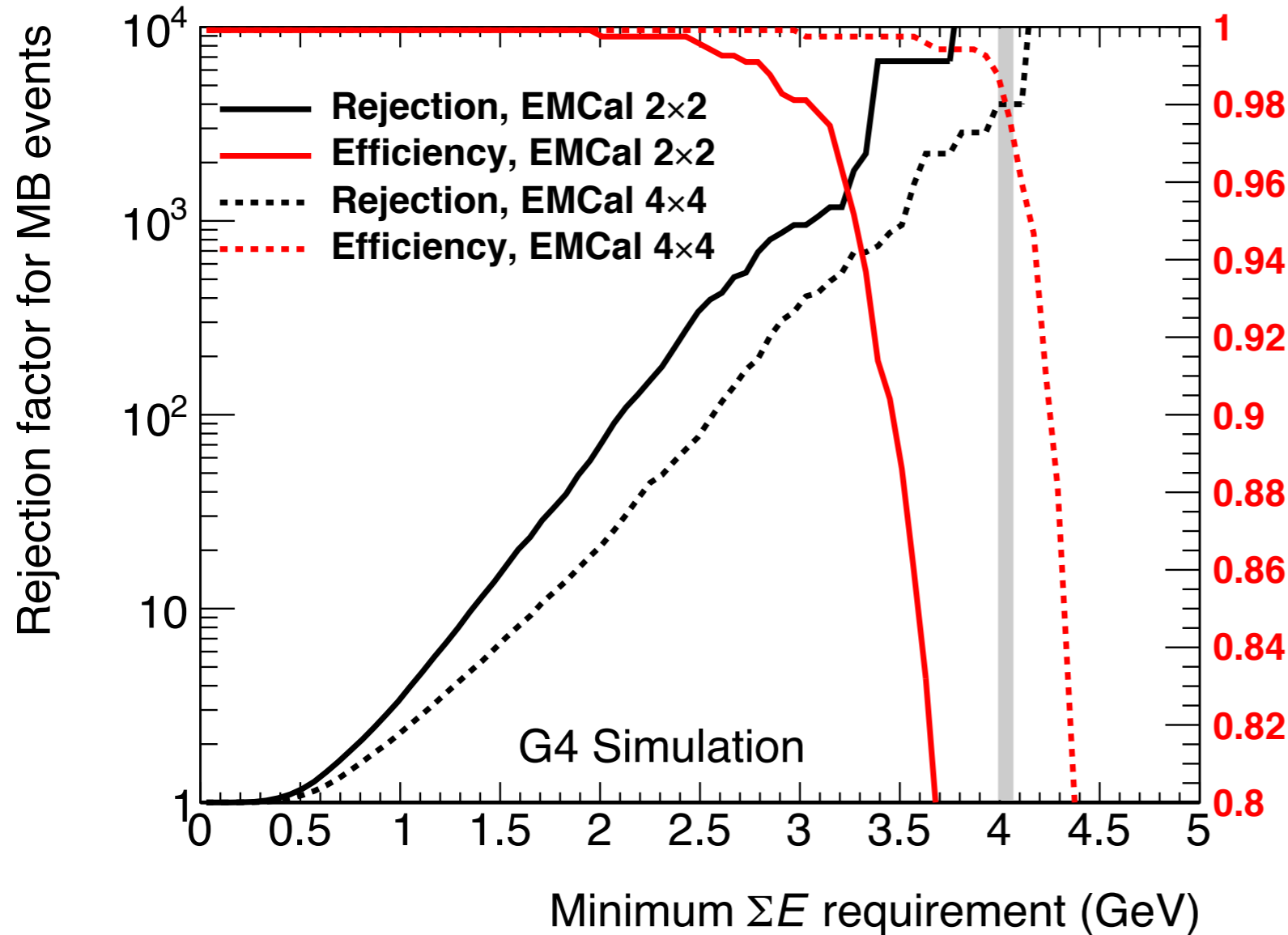
- • Solution: minimum energy in 2x2 or 4x4 sliding window of Δη×Δφ=0.025×0.025 EMCal towers

  ➜ sufficient **trigger efficiency** for E=4.7 GeV electrons, with **high rejection** in *p+p*

- • Allows detailed measurements of R_{AA} vs. N_{part}, p_T, y
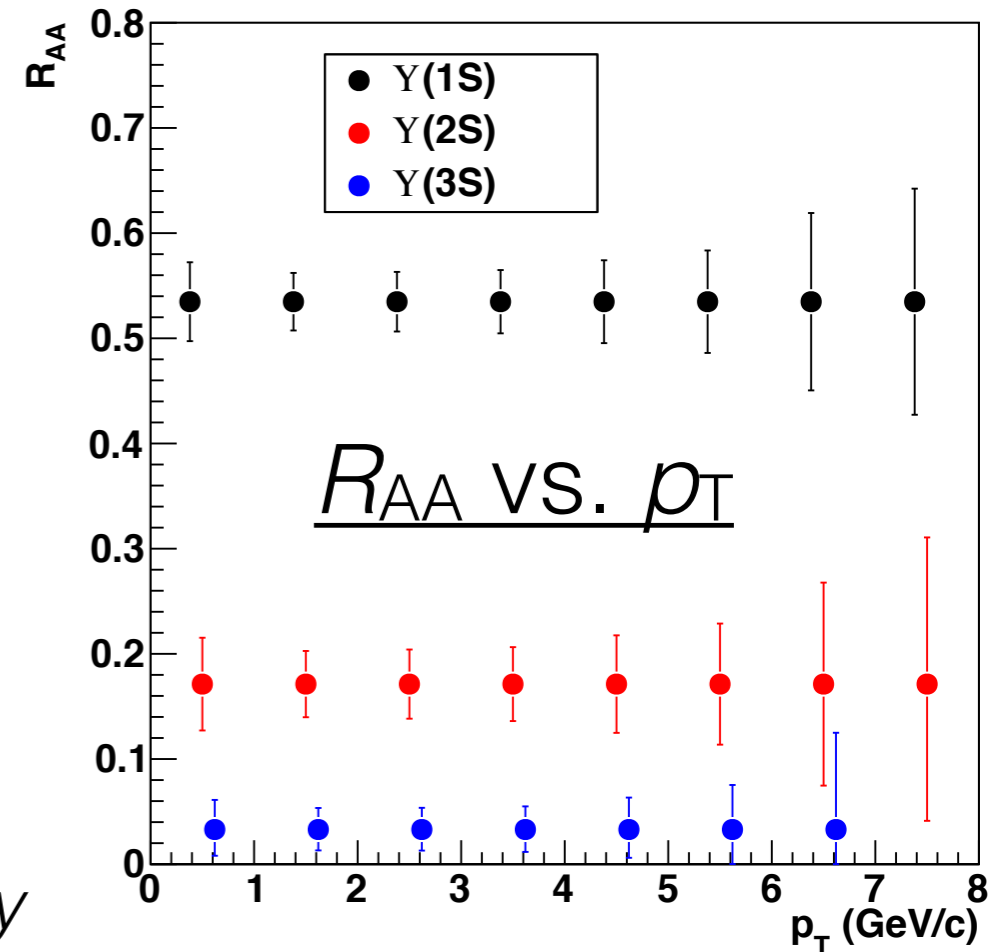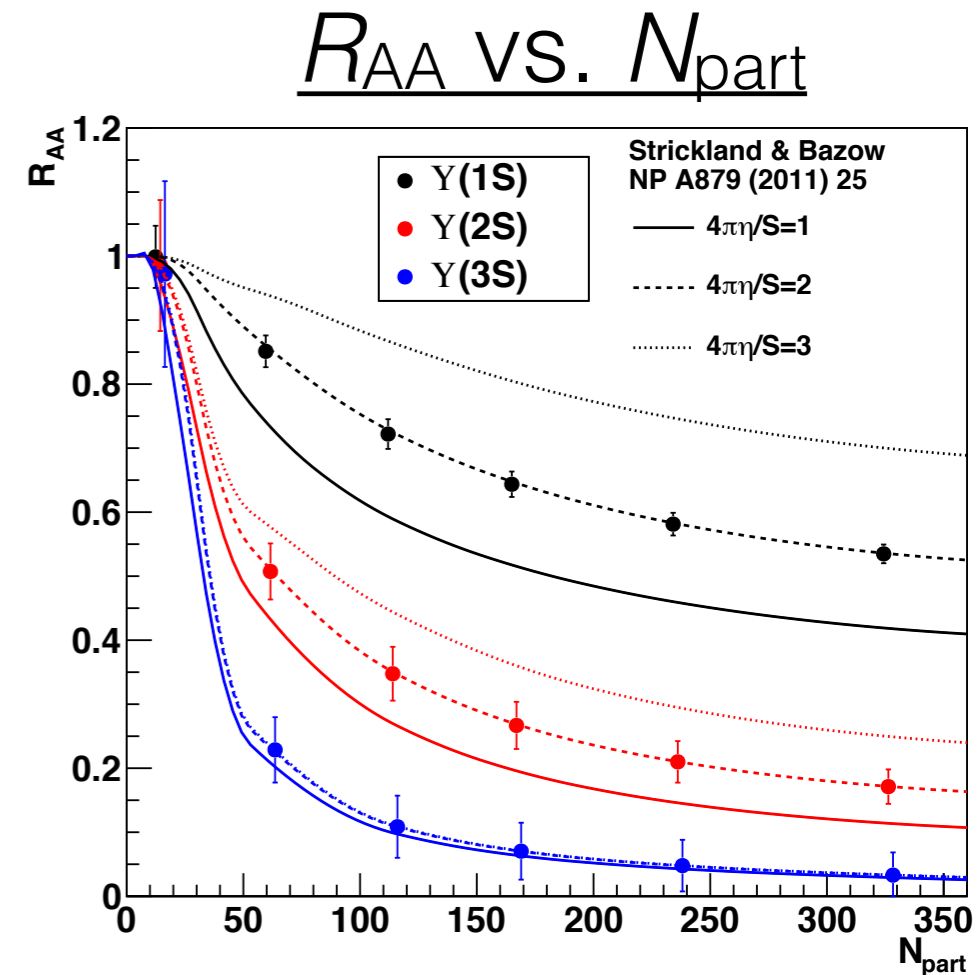
Upsilons: electron identification
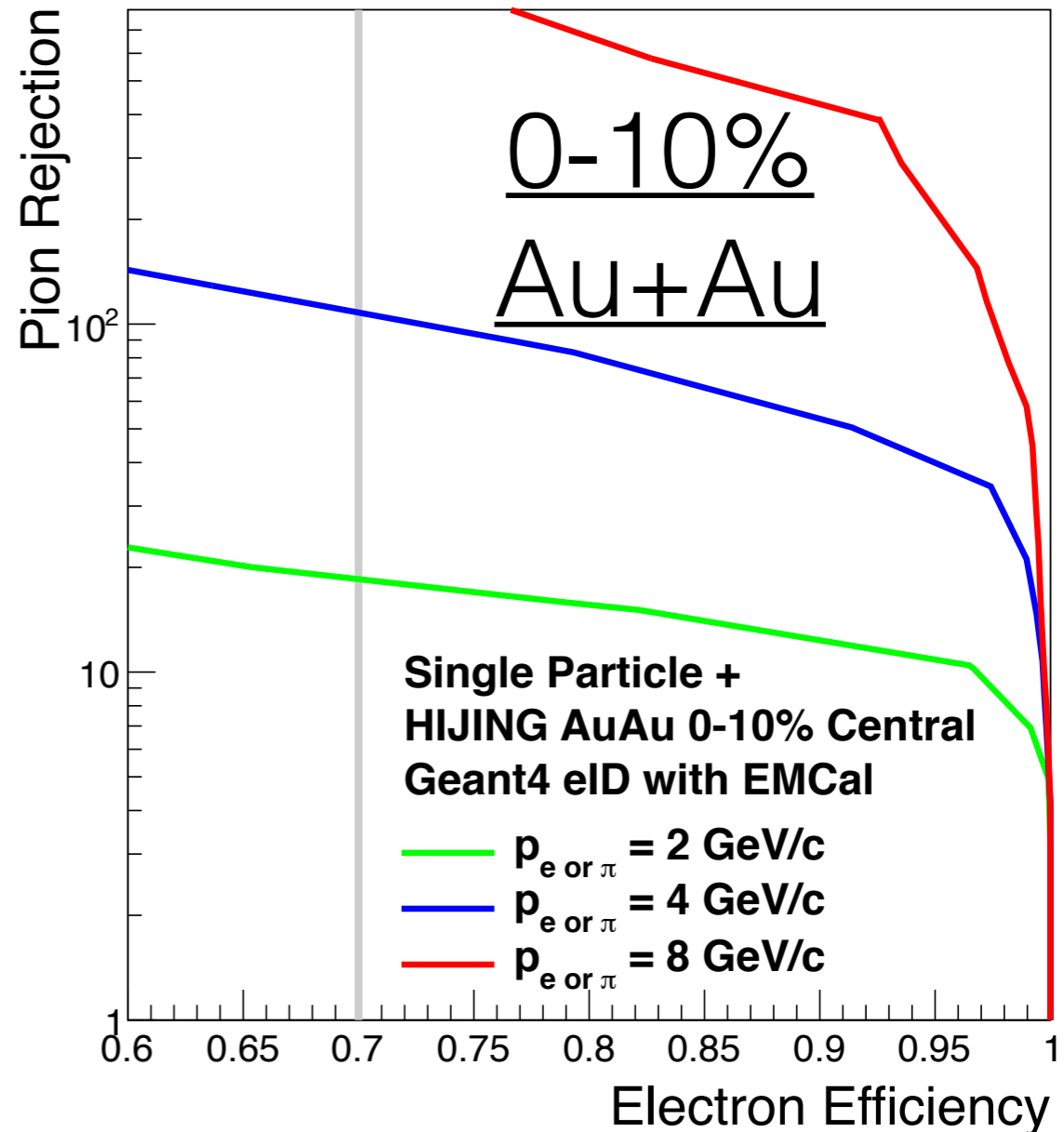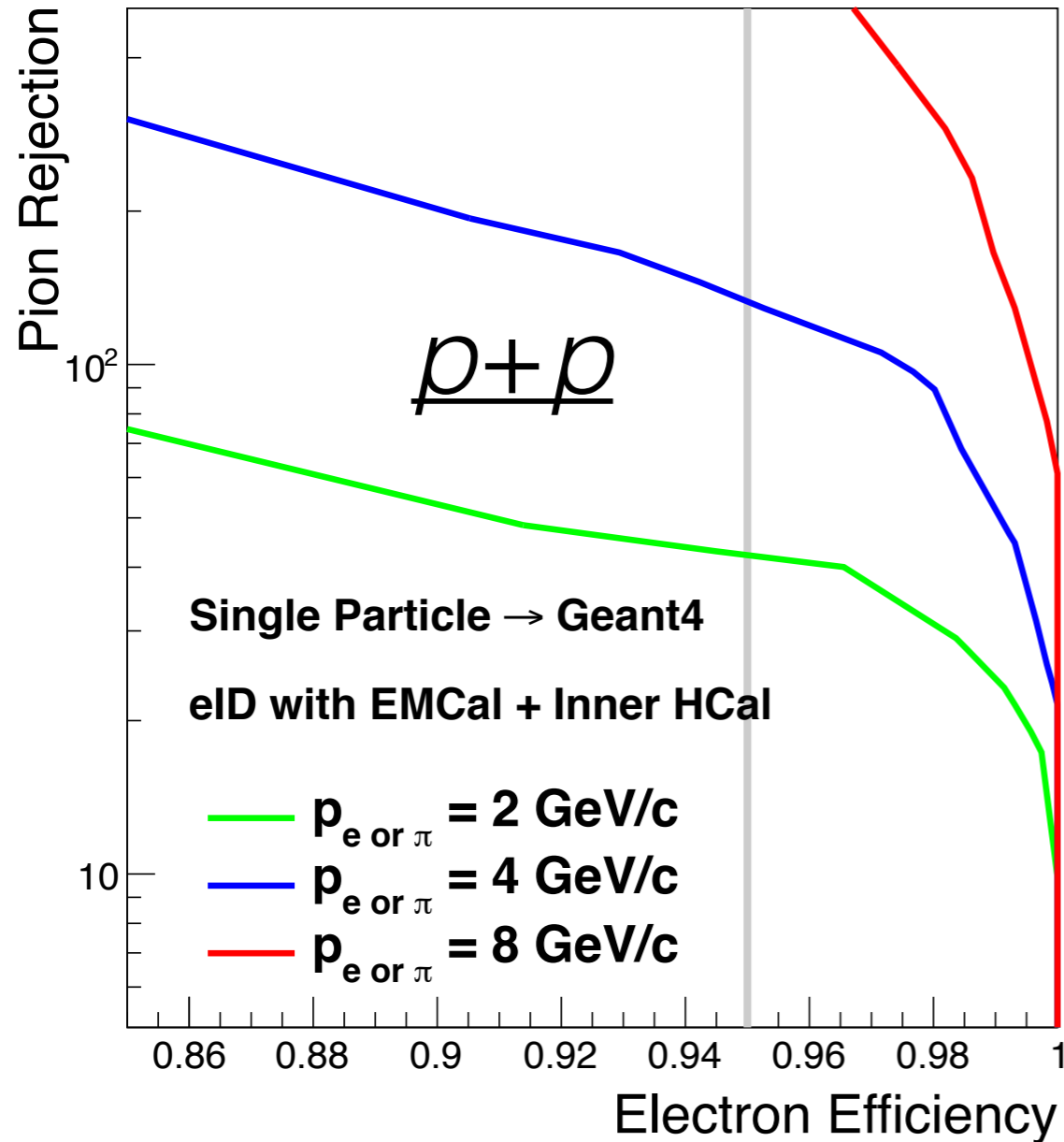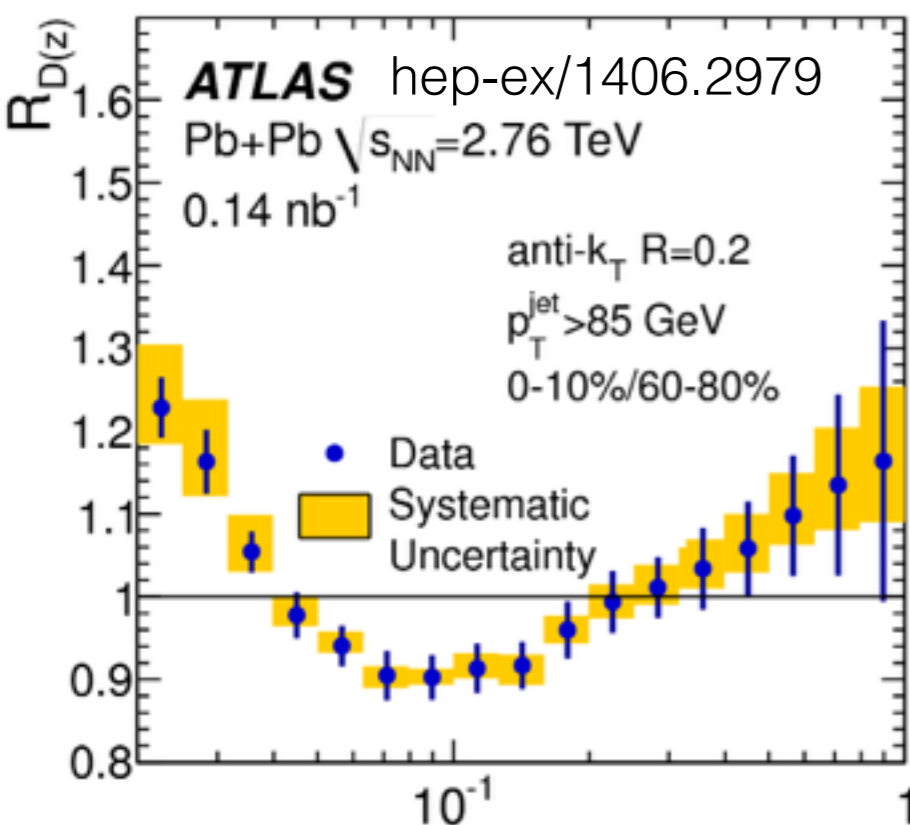

- Electron identification & charged pion rejection from:
  ➡ *matching* track momentum to *EMCal cluster energy*
  ➡ and *veto* on the presence of *inner HCal energy*
- For **4 GeV electrons**, 100:1 rejection with 95% efficiency (*p+p*) and 70% efficiency (central Au+Au)

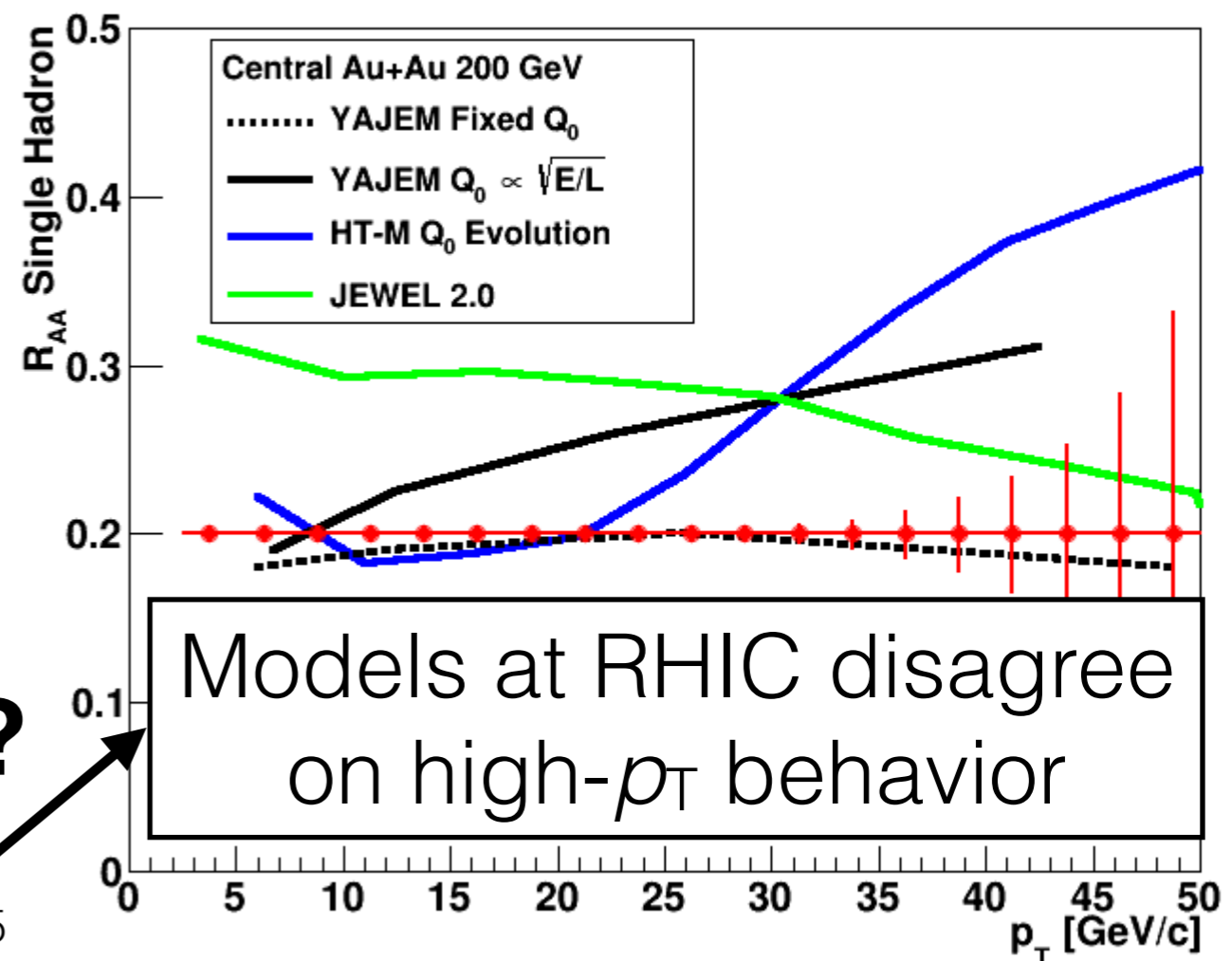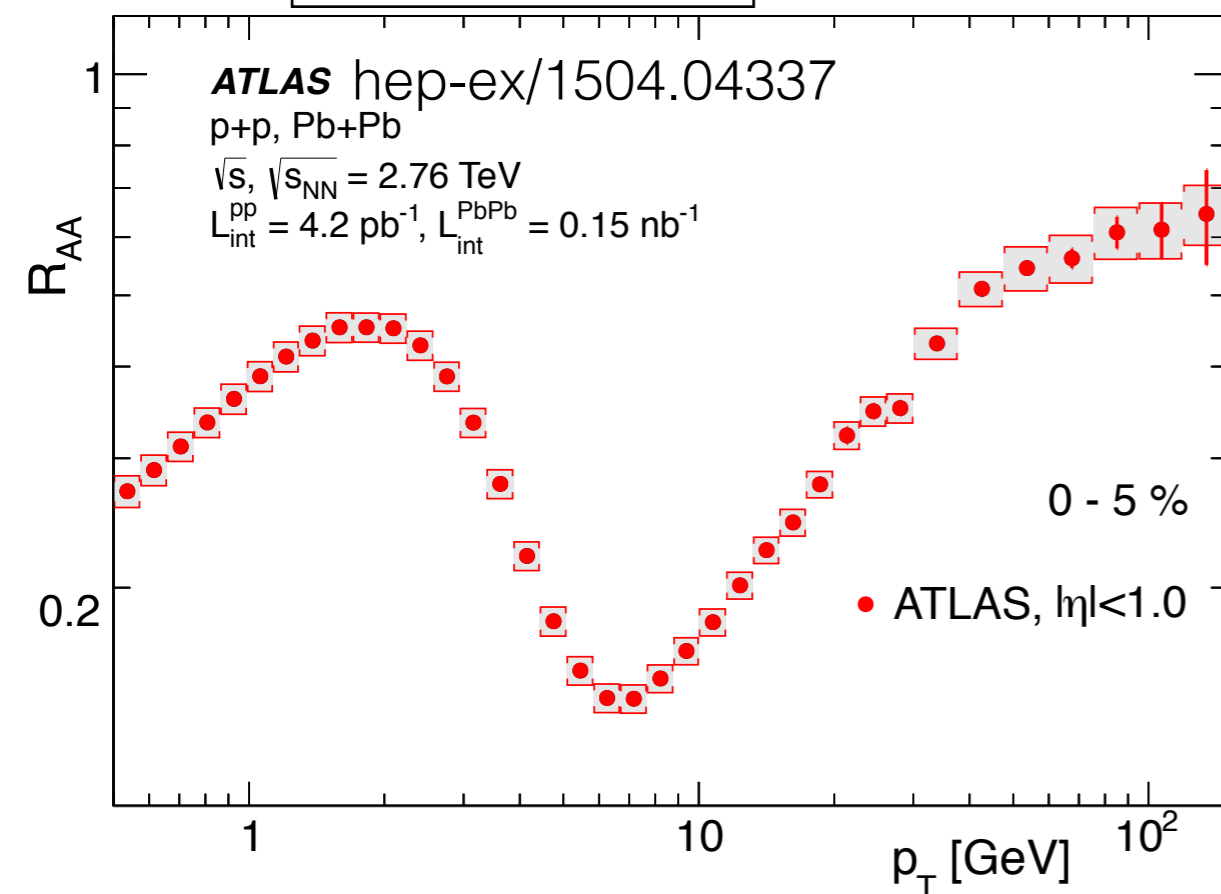# hadrons, fragmentation functions, *b*-jets

precision vertex tracking and high-p_T performance

hadrons and fragmentation functions

ATLAS hep-ex/1406.2979
Pb+Pb $\sqrt{s_{NN}}$=2.76 TeV
0.14 nb^{-1}

anti-k$_T$ R=0.2
p_T^{jet}>85 GeV
0-10%/60-80%

Data
Systematic Uncertainty

modification at all z values

- Fragmentation functions reveal *changes in the structure* of the jet

- Hadron spectra sensitive to, e.g. *virtuality evolution* in quenching

➡ both require tracking *performance at high-p_T*

ATLAS hep-ex/1504.04337
p+p, Pb+Pb
$\sqrt{s}$, $\sqrt{s_{NN}}$ = 2.76 TeV
L_{int}^{pp} = 4.2 pb^{-1}, L_{int}^{PbPb} = 0.15 nb^{-1}

0 - 5 %

● ATLAS, |η|<1.0

Rising/saturating R_{AA} at LHC

Central Au+Au 200 GeV
······ YAJEM Fixed Q$_0$
—— YAJEM Q$_0 \propto \sqrt{E/L}$
—— HT-M Q$_0$ Evolution
—— JEWEL 2.0

?

Models at RHIC disagree on high-p_T behavior

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hadrons and FF: tracking

3%

$$\frac{\Delta\ p_T}{p_T} = \sqrt{(1.18\%)^2 + (0.061\%)^2\ p_T^2}$$
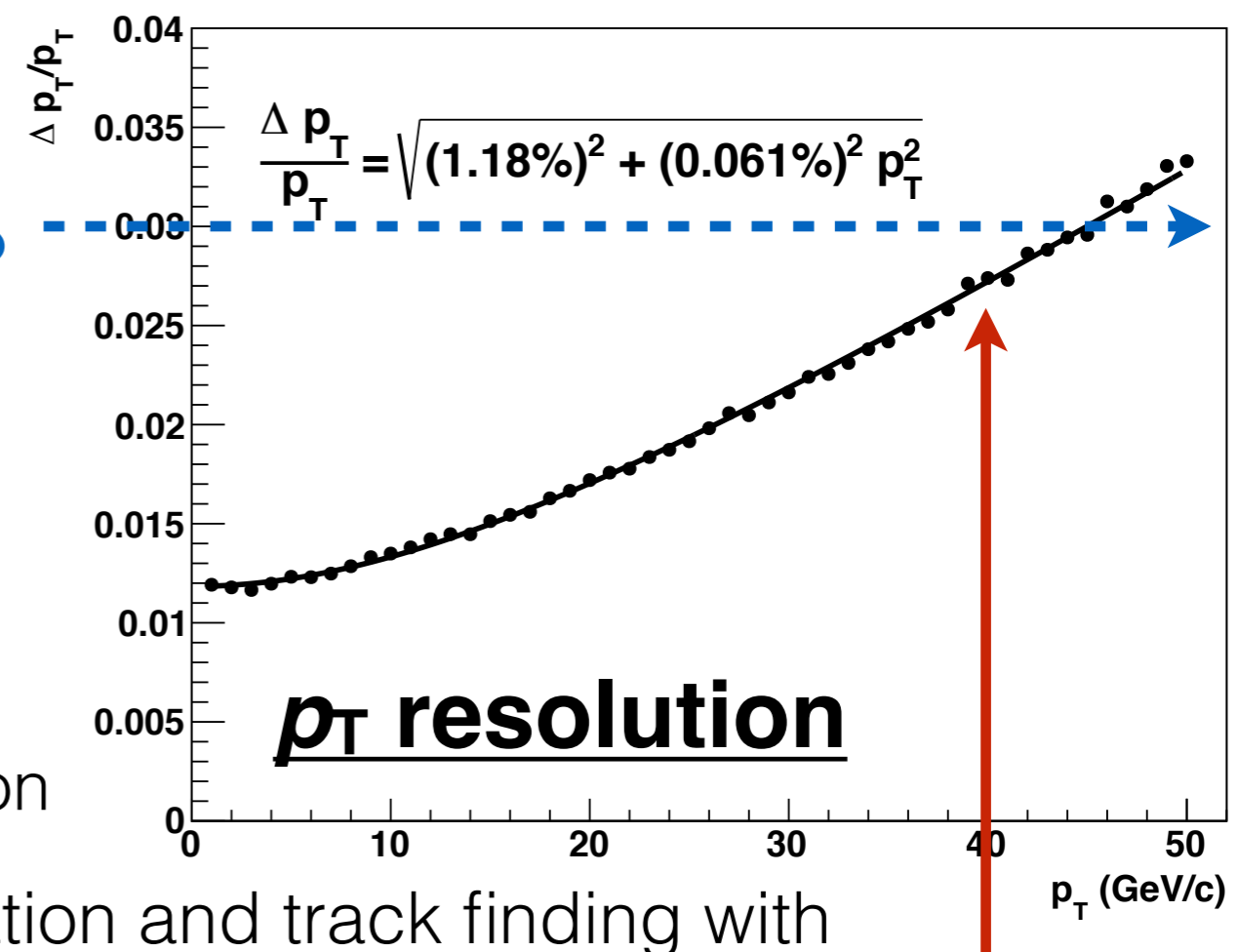
- Baseline tracking solution: reconfigured silicon vertex detector

  ➡ contains existing VTX Pixels, with new layers for resolution & pattern recognition

p_T **resolution**

40 GeV

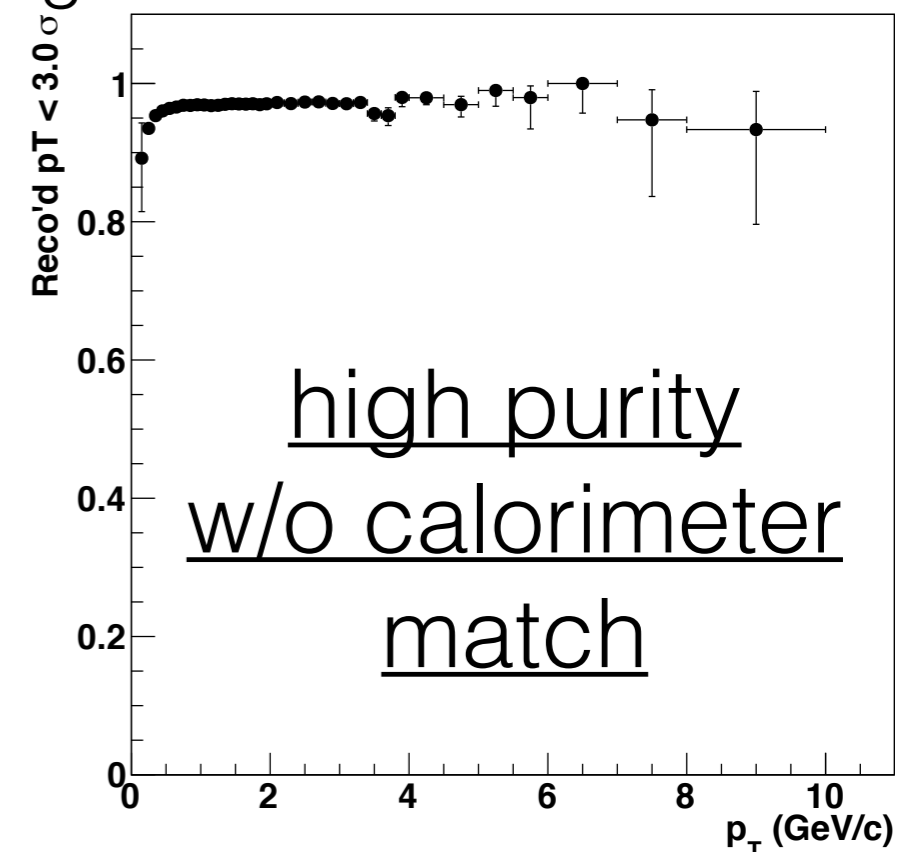- Substantial optimization of the configuration and track finding with full GEANT4 simulations to meet physics needs

  ➡ optimization of this design & TPC option also being considered

Reconstruction efficiency (3σ in η)

beam view

high efficiency

high purity w/o calorimeter match

Reco'd pT <3.0σ
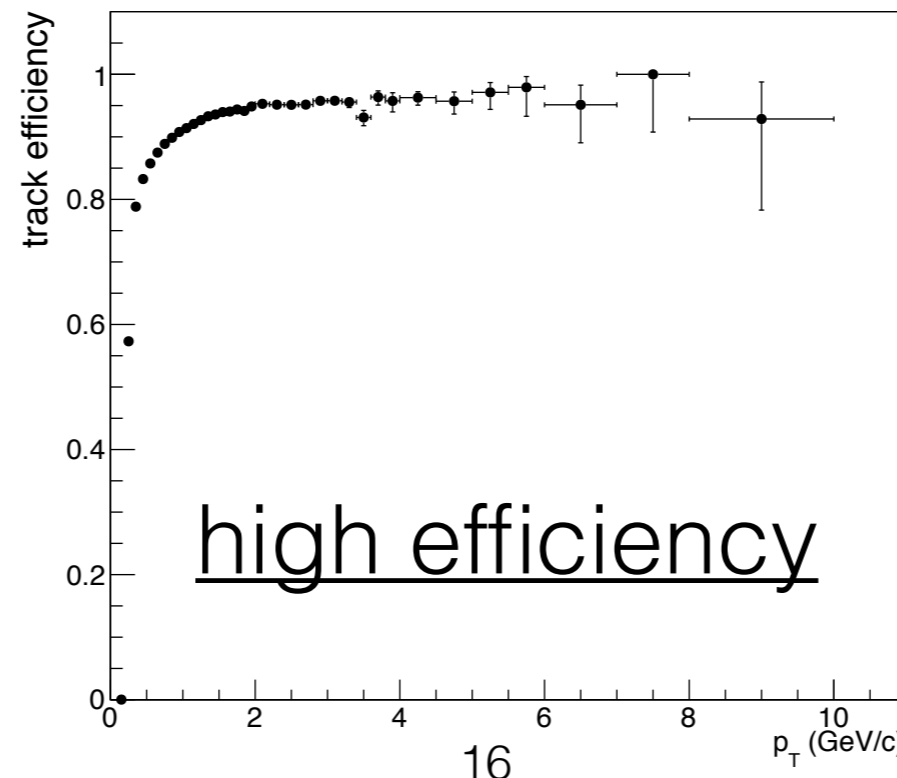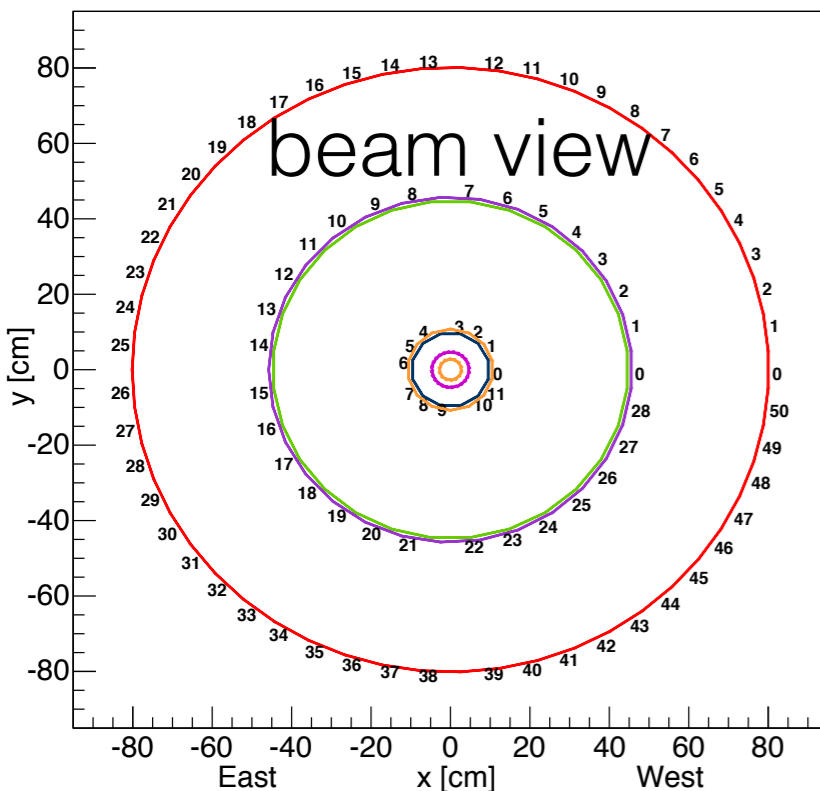
b-jet physics

- The quenching of heavy quark jets is different:

  ➡ suppression of radiation at small angles

  ➡ different sensitivity to *radiative* vs. *collisional* energy loss

- LHC measurements of *b*-jet R_{AA} are at > 80 GeV, consistent with light jets

  ➡ full *b*-jets at RHIC *probe needed kinematic range*

hep-ph/1306.0909
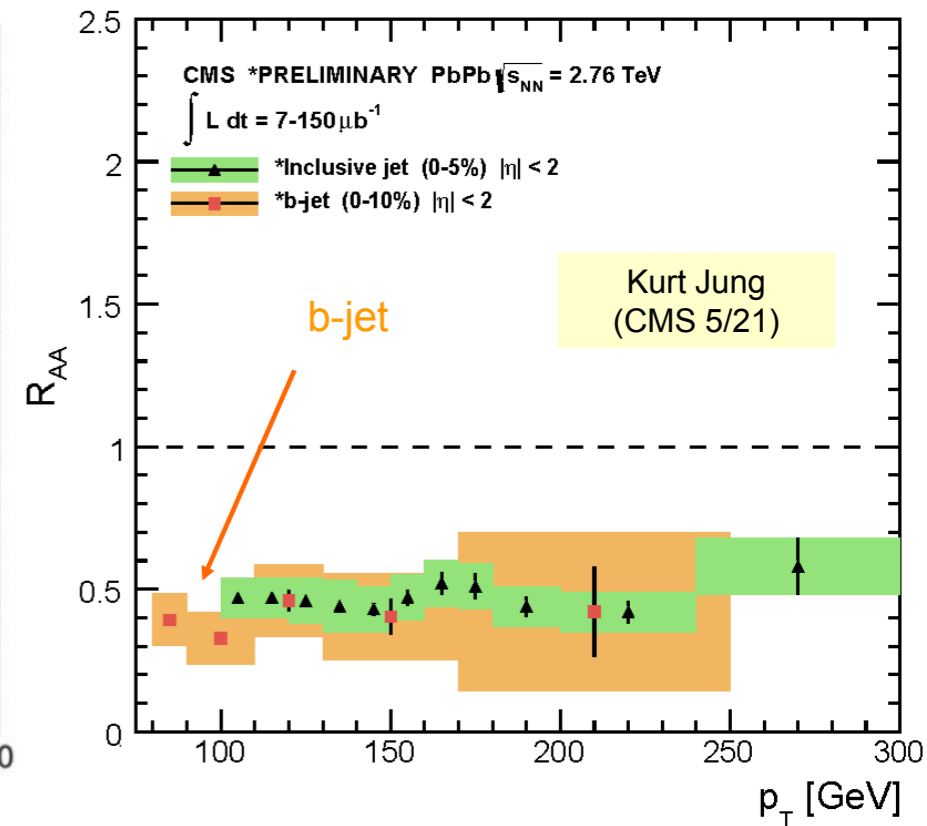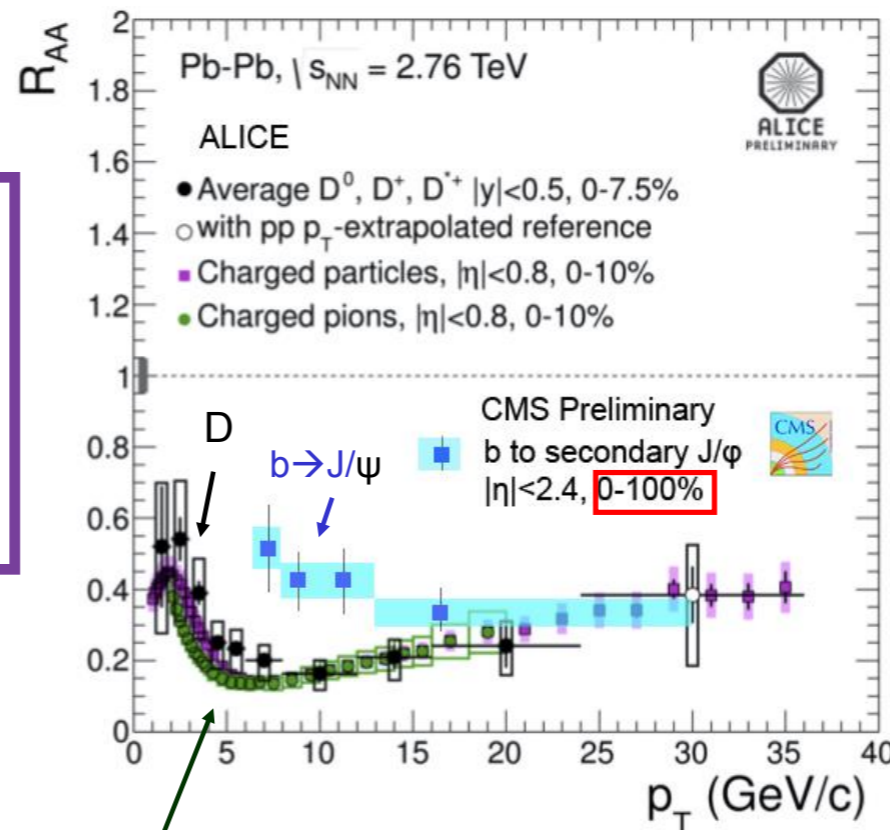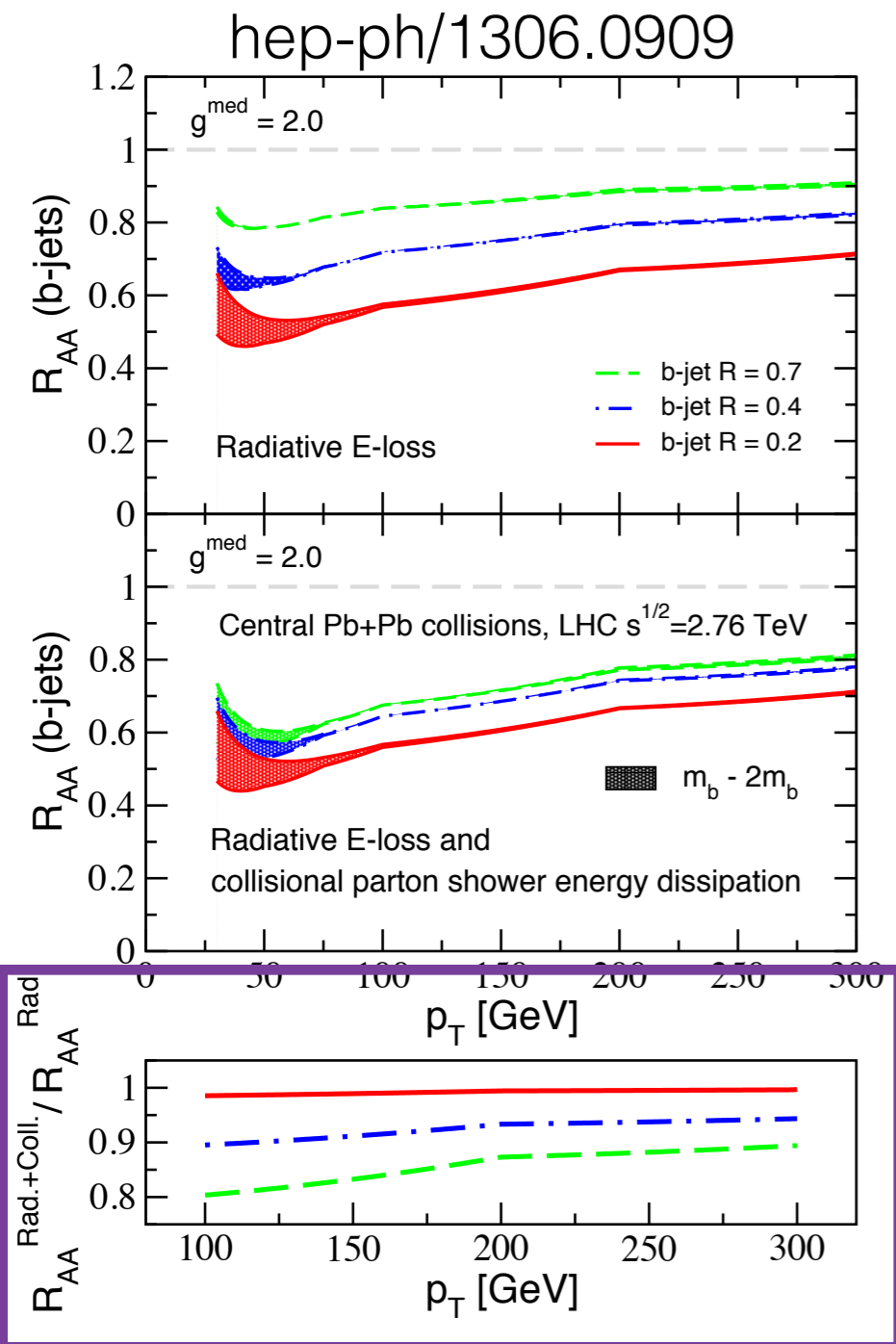
Ratio of R_{AA} with/without collisional E-loss

(QM'14 talk by Y-J. Lee)

b-jets: distance of closest approach

jet

tracks

Jet Axis

Secondary Vertex

Decay Length

DCA

Track
Impact
Parameter

Primary Vertex

DCA resolution in GEANT

p_T = 0.5-1.0 GeV/c
σ = 76.3 μm

p_T = 1.0-2.0 GeV/c
σ = 48.8 μm

p_T > 2.0 GeV/c
σ = 31.9 μm
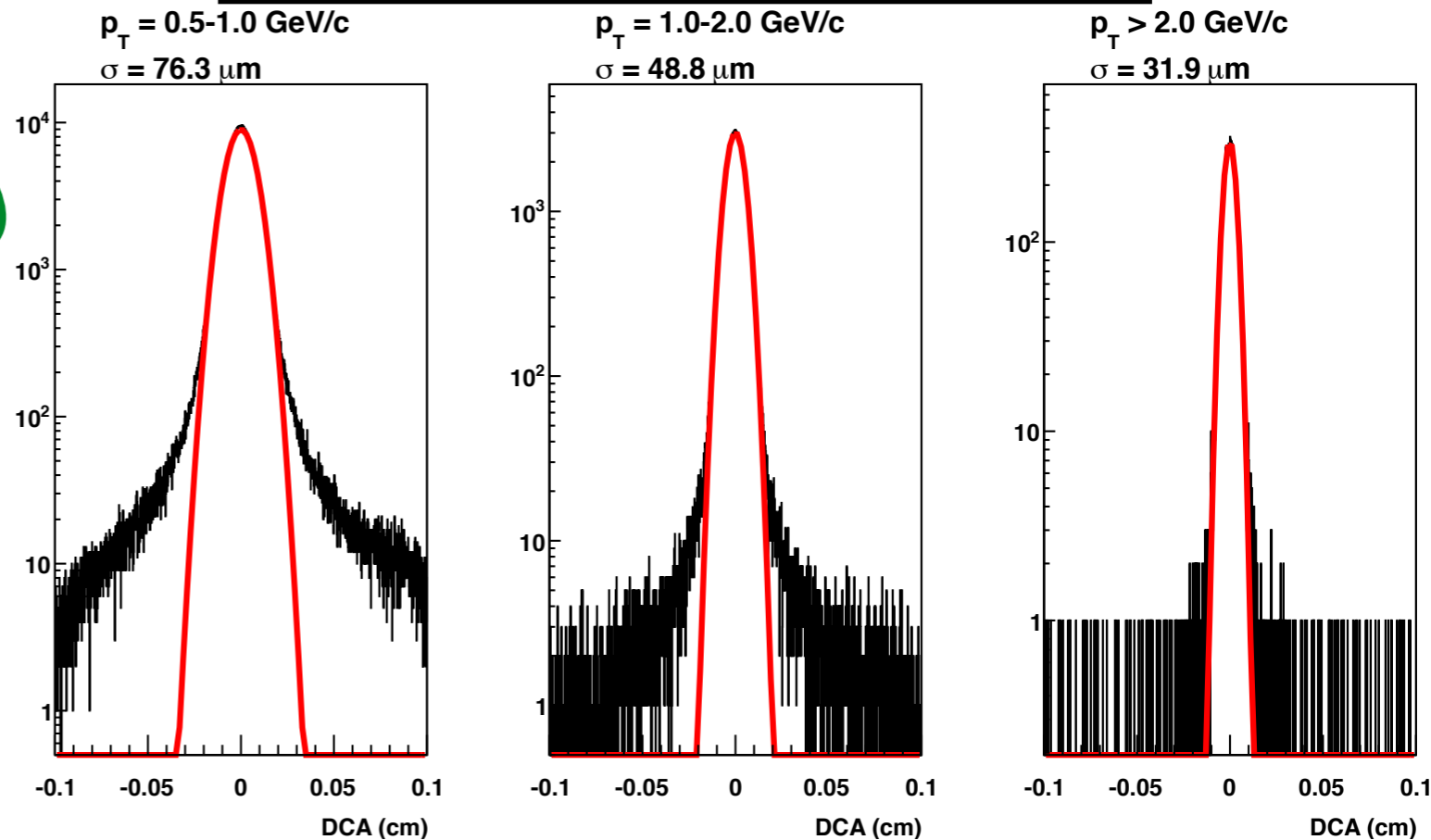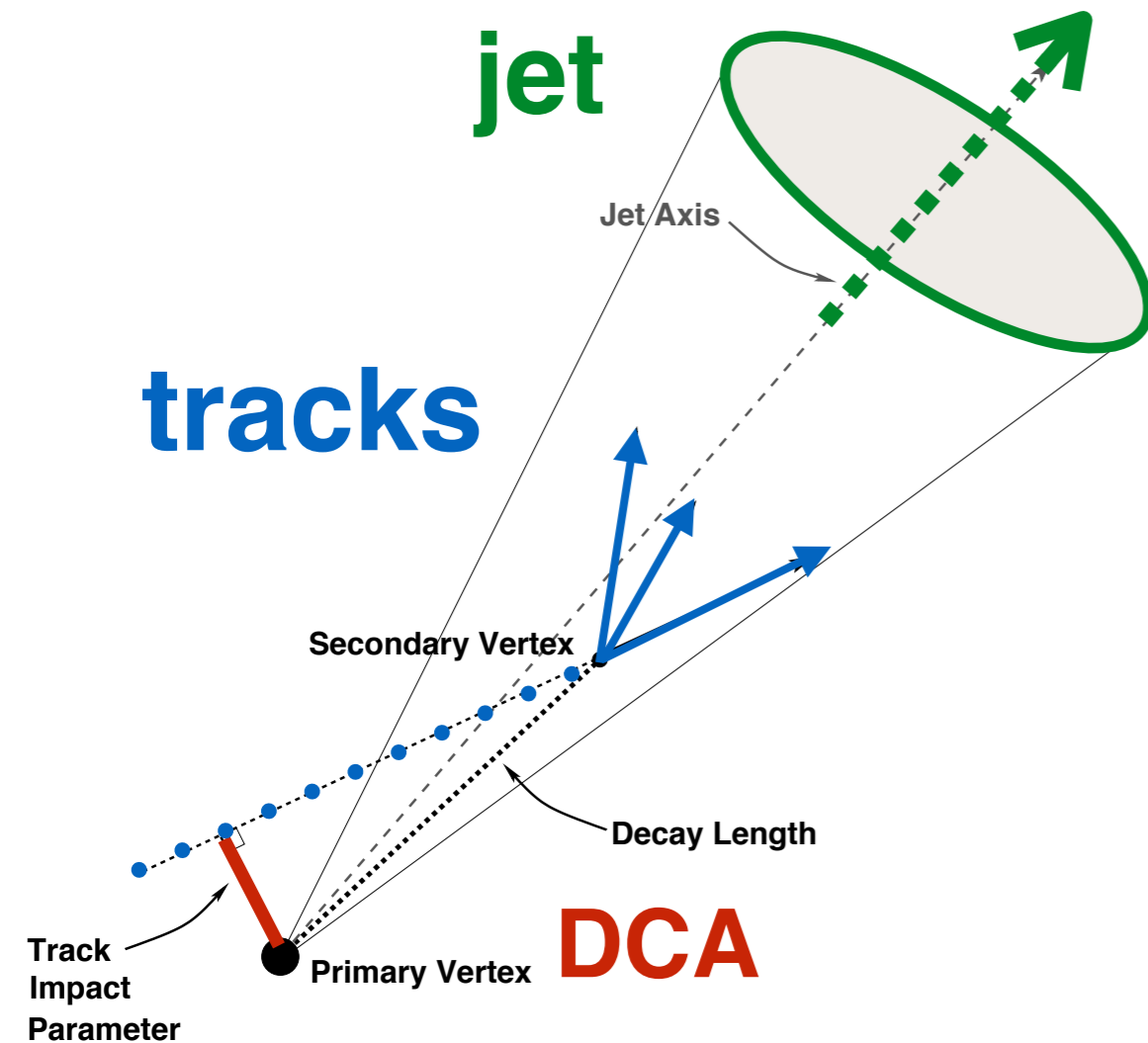
decreasing resolution with increasing p_T

- *b*-jets are "tagged" jet-by-jet by exploiting properties of *B* hadrons

  ➡ proof of principle method: select jets with *one or more tracks* which *do not point back to primary vertex*

- Precise measurement of distance of closest approach (DCA) required

  ➡ additionally, allows *D meson reconstruction without PID*

jet+X correlations

acceptance, rate,
electromagnetic calorimetry

jet+X correlations

Hadron Trigger

Jet + Track p$_T$ Cut Trigger

Ideal Jet Trigger
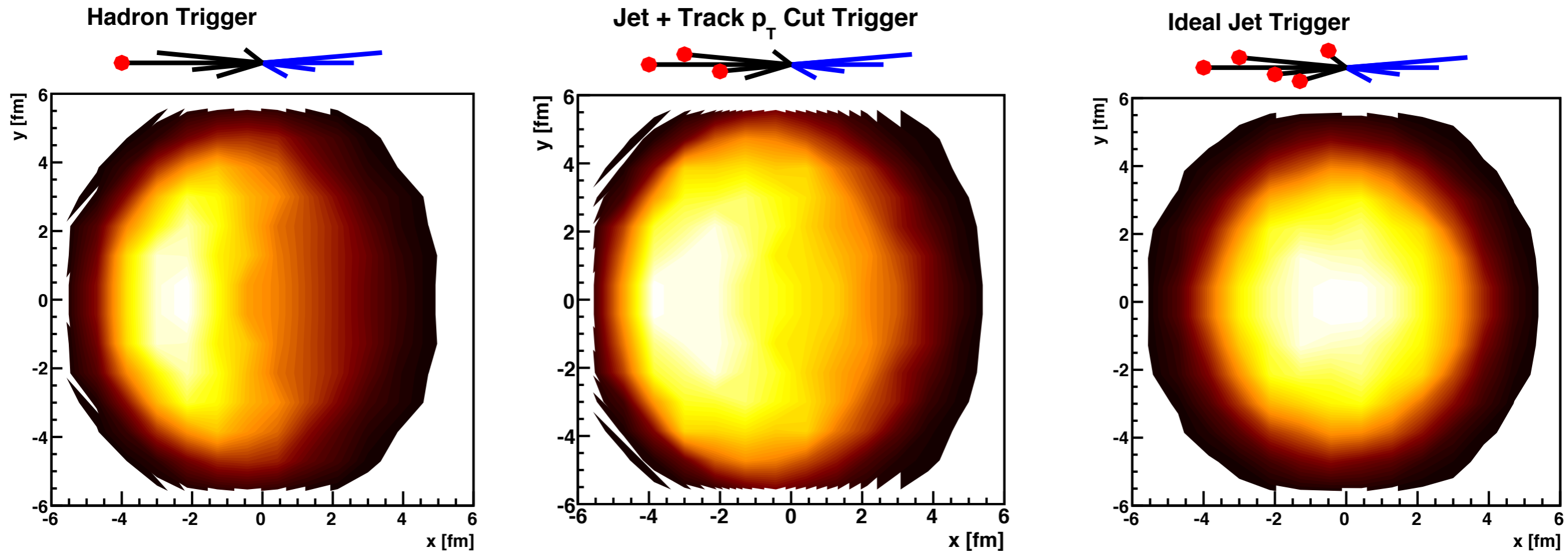
- Recent interest in "surface bias engineering" (and/or "flavor engineering") to examine _jets on the away side_ from a particular _near-side trigger object_

  ➡ photons, small-cone jets, high-p_T hadrons, etc.

- Large sample of minimum bias data crucial to exploring this physics

eje

PYTHIA+VNI, R=0.5 E$_{T1}$>120 E$_{T2}$>50 GeV
— Vacuum

PYTHIA+VNI T=350 MeV, R=0.2 E$_{T1}$>20.0
— Vacuum

dijet measurements

- Dijet asymmetry measurements are thought to have _strong sensitivity_ to descriptions of jet quenching

  ➡ crucial to vary _temperature, scale, and energy_ for full understanding

- sPHENIX acceptance |η|<1.0 ample for high-statistics measurements

LHC

Legend:
- PYTHIA+fastjet p+p
- MARTINI+fastjet Pb+Pb
- ATLAS p+p 7 TeV
- ATLAS Pb+Pb 0–10%
- Qin Pb+Pb

dN/dA_j vs A_j

RHIC

Legend:
- Qin p+p
- Qin Au+Au
- MARTINI p+p
- MARTINI Au+Au
- 0–10%, R = 0.4, E_1 >35 GeV, E_2 > 5 GeV

dN/dA_j vs A_j

PYTHIA-8 Jet anti-k_T R=0.2
- E_T > 20.0 GeV
- E_T > 30.0 GeV
- E_T > 40.0 GeV

Pseudorapidity

Fraction of Dijet/Single Accepted

η Acceptance
- |η| < 1.3
- |η| < 1.0
- |η| < 0.7

Trigger Jet E_T [GeV]

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Photon-jet physics

pQCD Rates

- π^0 (LHC 2.76 TeV) [R_{AA} suppressed]
- Direct γ (LHC 2.76 TeV)
- π^0 (RHIC 200 GeV) [R_{AA} suppressed]
- Direct γ (RHIC 200 GeV)

p+p Ratios (NLO pQCD)
- Direct γ/π^0 (RHIC 200 GeV)
- PHENIX Data (RHIC 200 GeV)
- Direct γ/π^0 (LHC 2.76 TeV)

Au+Au / Pb+Pb Ratios (Scaled NLO pQCD)
- Direct γ/π^0 (RHIC 200 GeV)
- PHENIX Data (RHIC 200 GeV)
- Direct γ/π^0 (LHC 2.76 TeV)

g_{med}= 2.0(2) Rad.+Col.
p+p NLO
Pb+Pb CNM

$S^{1/2}$=200 GeV
$|\psi|>7/8\,\pi$ R=0.3
P_T^{Jet}>10 GeV , P_T^γ>30 GeV

hep-ph/ 1207.5177

$z_{J\gamma}$

Photon-jet vs. reaction plane!

Au+Au 30-50%   p+p γ-jet E_T^γ > 30 GeV

$60° < \Delta\phi < 90°$

$30° < \Delta\phi < 60°$

$0° < \Delta\phi < 30°$

$x_{J\gamma} = p_T^{jet} / E_T^\gamma$

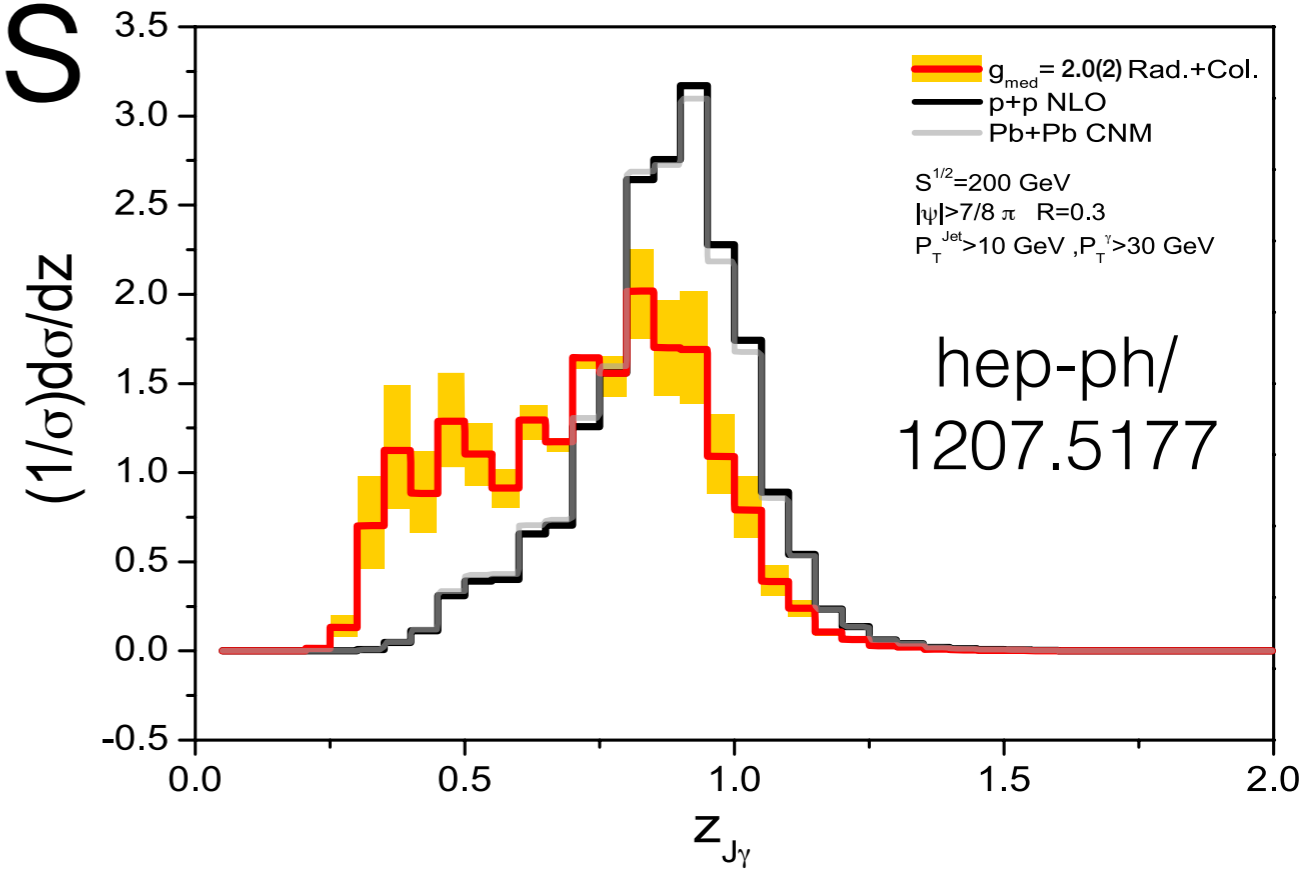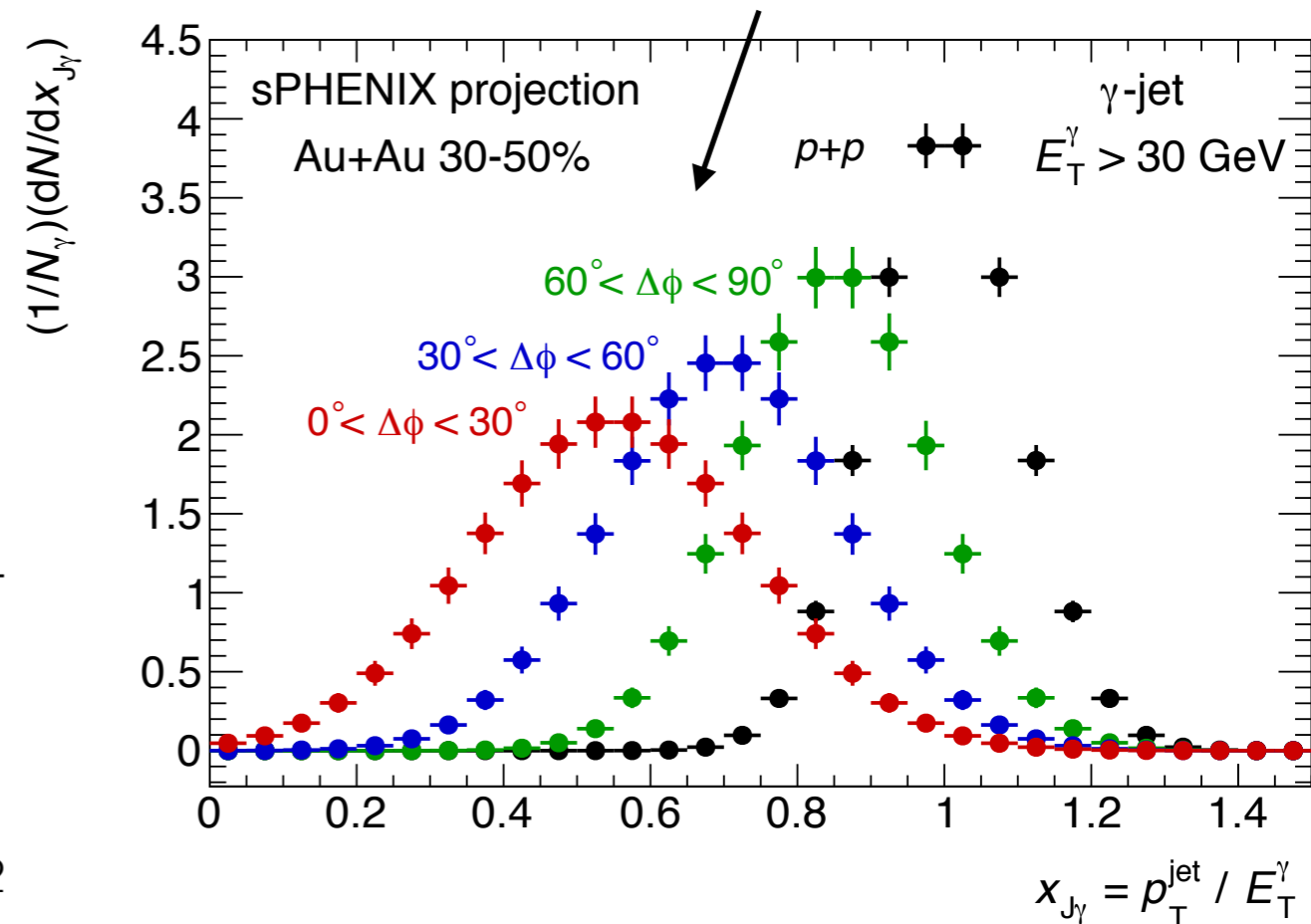High γ/π^0 ratio at RHIC and finely segmented (0.025x0.025) EMCal

➡ allows photon identification to low p_T

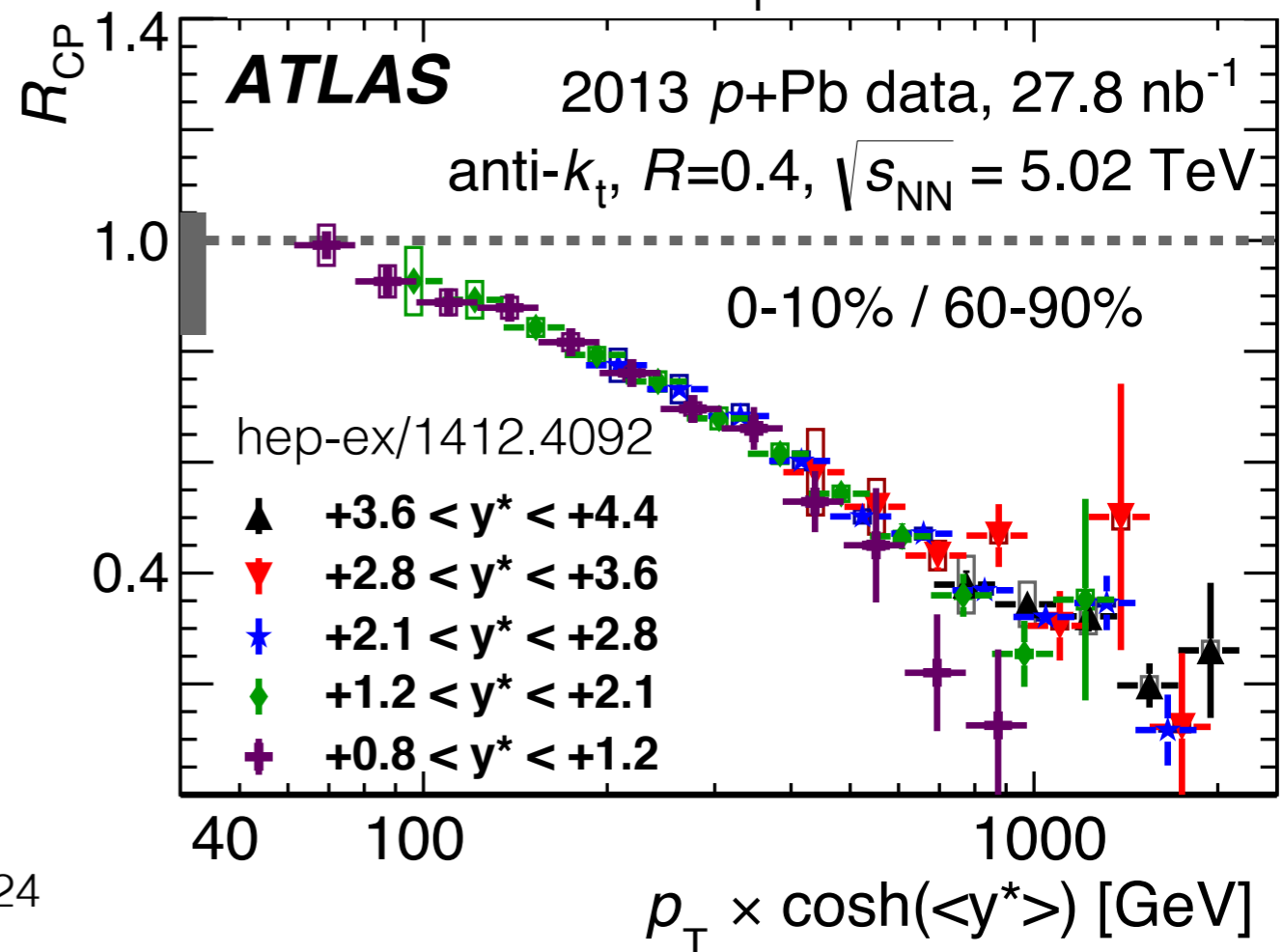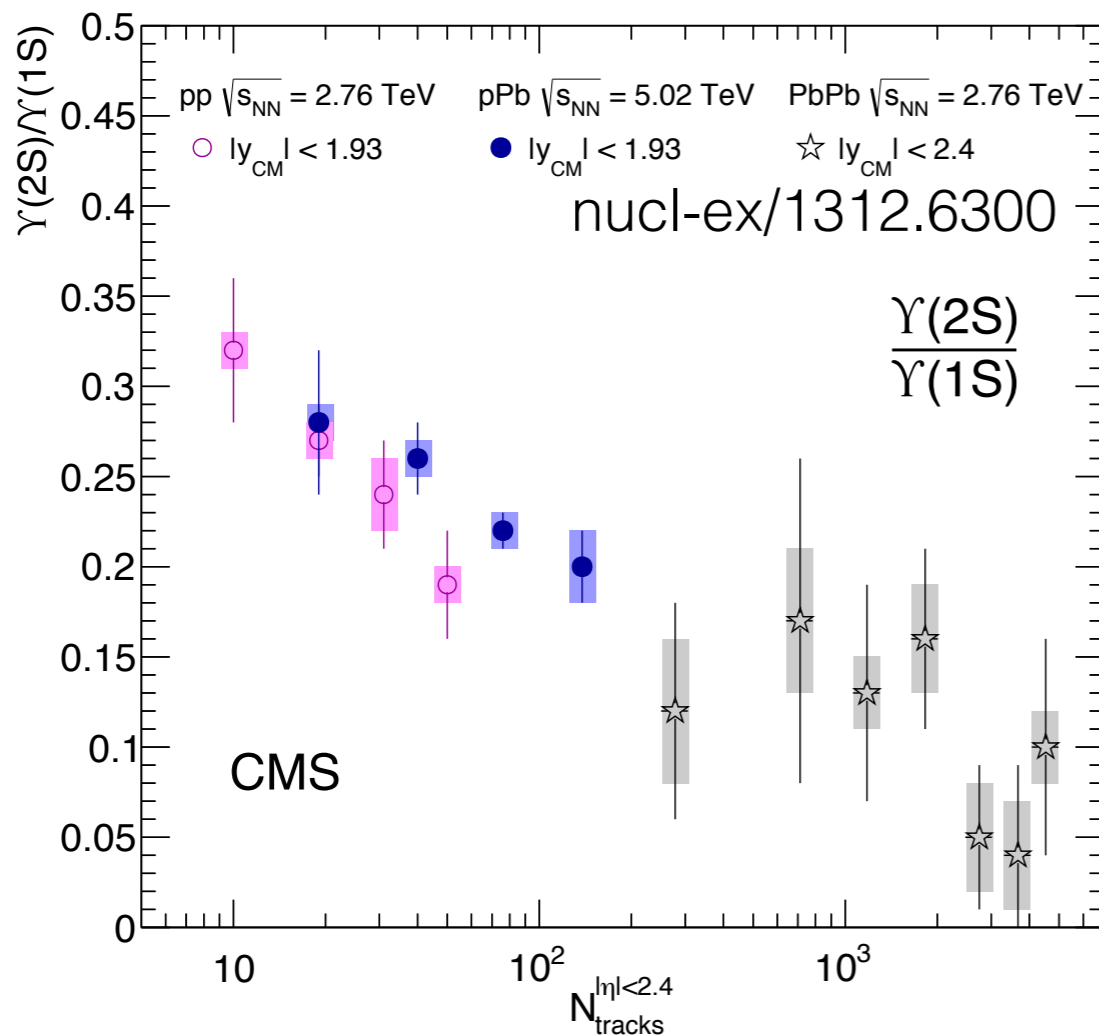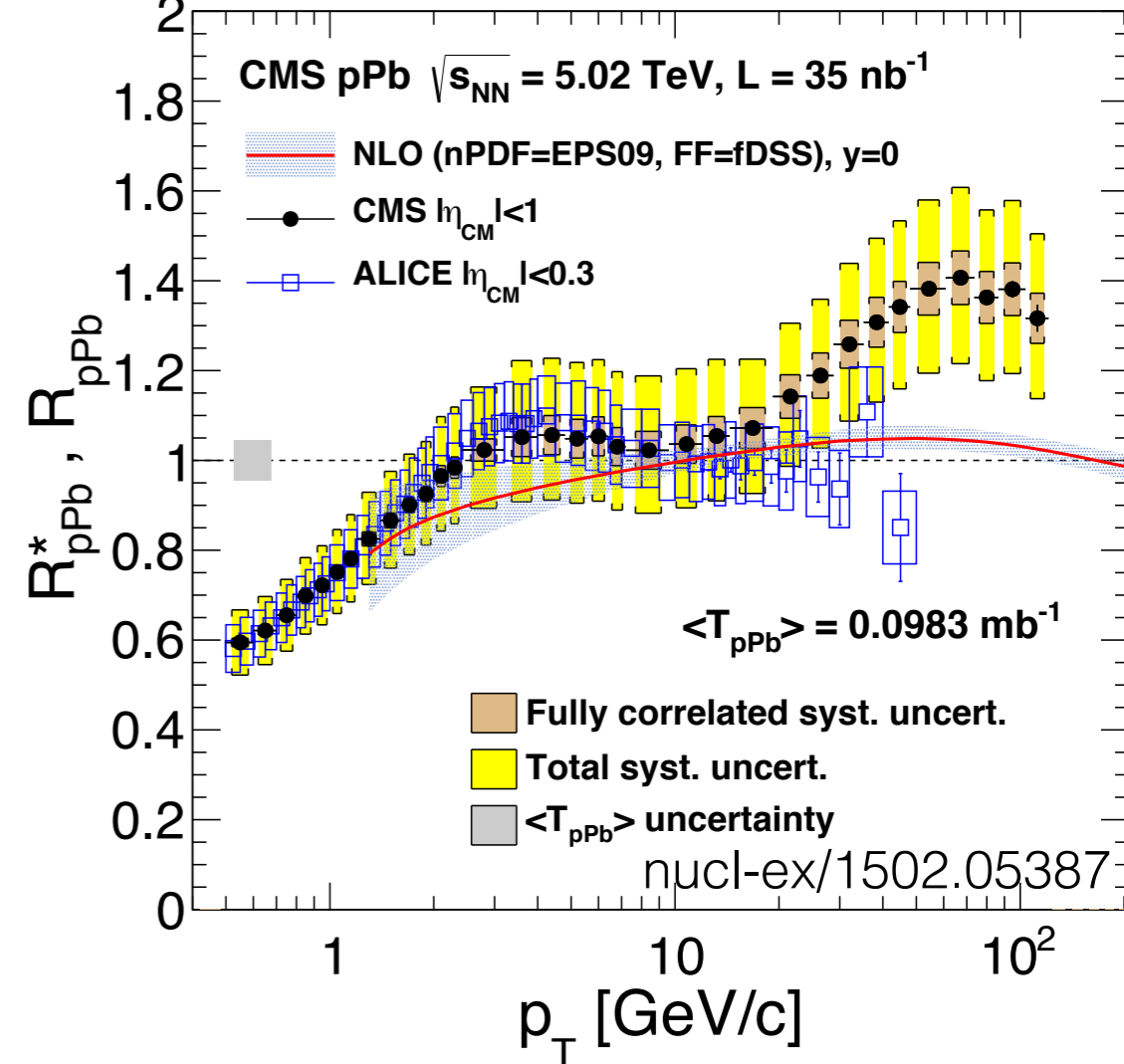High sPHENIX rate and triggering allow for differential measurements
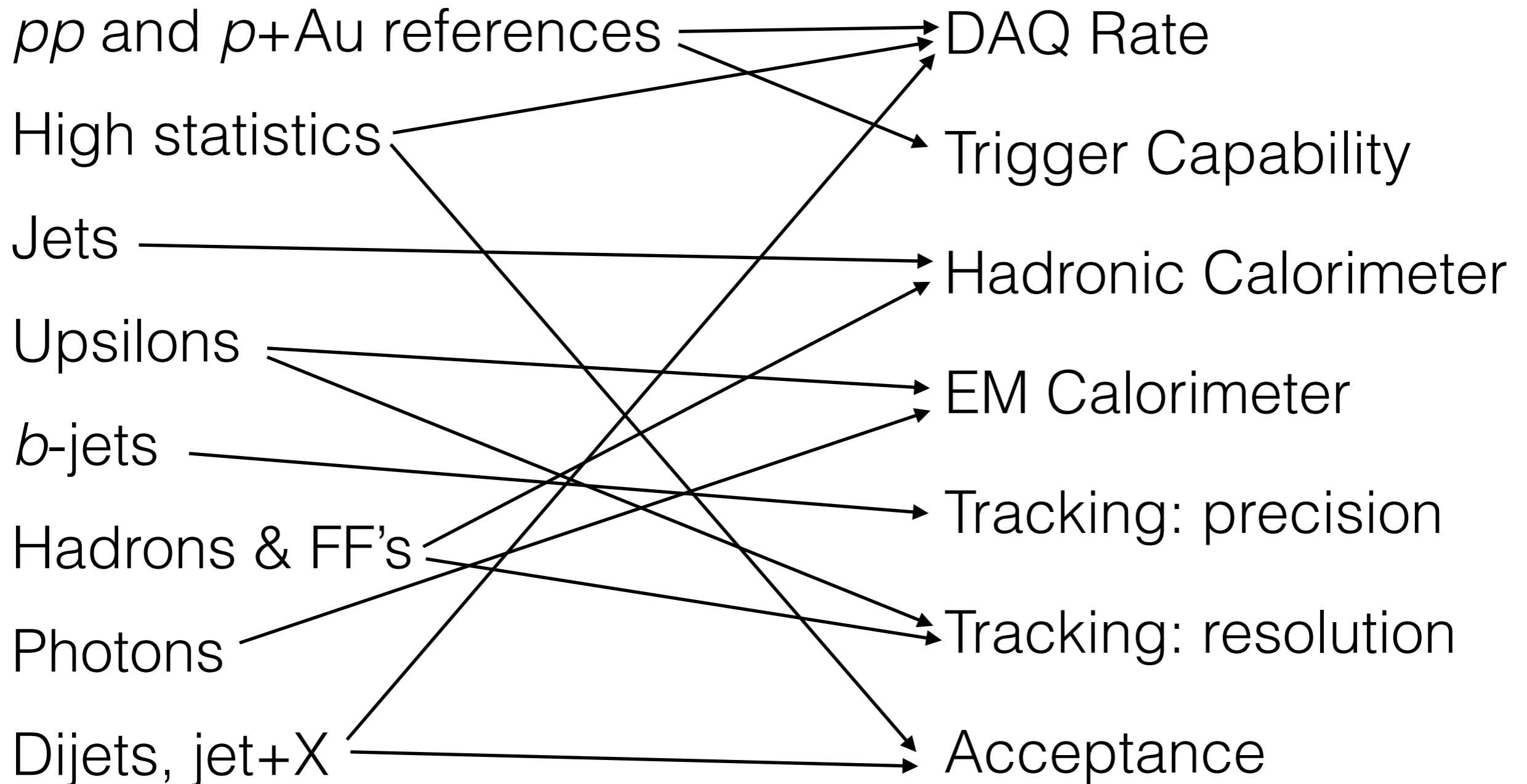
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p+Au physics

… not just a reference system anymore

sPHENIX is capable of exploring novel phenomena in p+Au collisions

➡ Enhancement in **high-p_T charged particles**

➡ Scaling of **jet centrality dependence** with proton Bjorken-x

➡ Multiplicity-dependent **suppression of $\Upsilon(2S)/\Upsilon(1S)$** in all systems

CMS pPb $\sqrt{s_{NN}}$ = 5.02 TeV, L = 35 nb^{-1}

NLO (nPDF=EPS09, FF=fDSS), y=0

CMS $|\eta_{CM}|$<1

ALICE $|\eta_{CM}|$<0.3

$<T_{pPb}>$ = 0.0983 mb^{-1}

Fully correlated syst. uncert.

Total syst. uncert.

$<T_{pPb}>$ uncertainty

nucl-ex/1502.05387

R^*_{pPb} , R_{pPb}

p_T [GeV/c]

pp $\sqrt{s_{NN}}$ = 2.76 TeV $|y_{CM}|$ < 1.93
pPb $\sqrt{s_{NN}}$ = 5.02 TeV $|y_{CM}|$ < 1.93
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV $|y_{CM}|$ < 2.4

nucl-ex/1312.6300

$\frac{\Upsilon(2S)}{\Upsilon(1S)}$

CMS

$\Upsilon(2S)/\Upsilon(1S)$

$N^{|\eta|<2.4}_{tracks}$

ATLAS   2013 p+Pb data, 27.8 nb^{-1}
anti-k_t, R=0.4, $\sqrt{s_{NN}}$ = 5.02 TeV

0-10% / 60-90%

hep-ex/1412.4092

▲ **+3.6 < y* < +4.4**
▼ **+2.8 < y* < +3.6**
★ **+2.1 < y* < +2.8**
◆ **+1.2 < y* < +2.1**
✚ **+0.8 < y* < +1.2**

R_{CP}

$p_T \times \cosh(<y^*>)$ [GeV]

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Physics drivers for design

pp and p+Au references   DAQ Rate

High statistics   Trigger Capability

Jets   Hadronic Calorimeter

Upsilons   EM Calorimeter

b-jets   Tracking: precision

Hadrons & FF's   Tracking: resolution

Photons

Dijets, jet+X   Acceptance

+ Review Committee guidance

… not to mention cost and schedule considerations